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Overview of EMF 22 U.S. transition scenarios

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ABSTRACT

The Energy Modeling Forum 22 study included a set of U.S. transition scenarios designed to bracket a range of potential U.S. climate policy goals. Models from the six teams that participated in this part of the study include models that have been prominently involved in analyzing proposed U.S. climate legislation, as well as models that have been involved in the Climate Change Science Program and other parts of this EMF 22 study. This paper presents an overview of the results from the U.S. transition scenarios, and provides insights into the comparison of results from the participating models.

1. Introduction

There have been a variety of different policy measures proposed to limit greenhouse gas (GHG) emissions in the United States; the most prominent of them have featured a broad cap-and-trade system as the central policy mechanism. Recent cap-and-trade proposals have put forward limits through the year 2050 and have featured banking of allowances over time and limited borrowing. Much of the focus has been on a cap set to 20% or less of current emissions by 2050, gradually reducing the amount of allowances over time. However, the actual level of domestic reduction that would occur depends on the extent to which external credits are allowed into the system and their availability. Actual domestic emissions reductions could be much less under some proposals that allow as much as 2 billion metric tons of credits per year from outside the system (e.g. H.R. 2454). The EMF 22 exercise developed three paths of allowance availability that would limit cumulative emissions through 2050. Interesting questions that are addressed include: (1) what are the costs of different levels of emissions reductions? (2) How will the reductions be allocated across time? (3) How will reductions be allocated across sectors? And (4) what are the implications of climate policy for the energy producers and consumers?

The EMF 22 U.S. transition scenarios study explores these questions through a comparison of results from six modeling teams across three standardized climate policy scenarios. Each modeling team was required to provide results related to economics, emissions, and energy systems for a reference scenario and three policy scenarios. Modelers were free to make their own decisions on demographics, baseline energy consumption, technology availability, and technology cost.

Section 2 details the study design. This section includes a list of modeling teams and scenarios, as well as a description of how these scenarios relate to existing U.S. congressional bills and the international component of the EMF 22 study. Sections 3, 4, and 5 provide results from the study on emissions pathways, energy systems, and economic indicators, respectively. Section 6 summarizes the results, and Section 7 provides a preview of issues explored by the individual modeling teams in their papers.

2. Overview of the study design

2.1. Modeling teams

Six modeling teams completed the U.S. transition scenarios in the EMF 22 study; the models include: the Applied Dynamic Analysis of the Global Economy model (ADAGE) from the Research Triangle Institute; the Emissions Predictions and Policy Analysis model (EPPA) from the Massachusetts Institute of Technology; the Model for Emissions Reductions in the Global Environment (MERGE), from the Electric Power Research Institute; MiniCAM, from the Pacific Northwest National Laboratory/Joint Global Change Research Institute; the Multi-Region National Model–North American Electricity and Environment Model (MRN–NEEM), from Charles River Associates; and the Intertemporal General Equilibrium Model (IGEM), from Dale Jorgenson Associates. These models have been widely used for analysis of U.S. climate change policy. The ADAGE and IGEM models have supported the Environmental Protection Agency in its analyses of proposed climate change legislation such as the Lieberman–Warner Climate Security Act of 2008 (S. 2191), and the American Clean Energy

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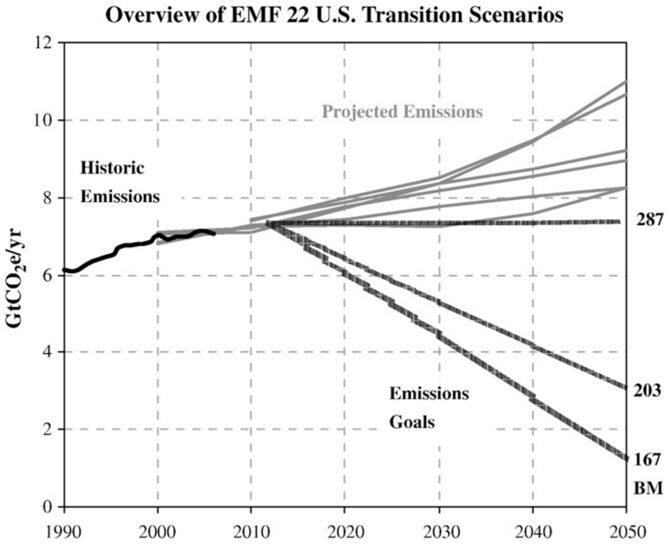

Fig. 1. Historic and projected reference scenario emissions versus emissions goals.

and Security Act of 2009 (H.R. 2454). The MRN–NEEM model has been used by Charles River Associates for numerous analyses, including its own analyses of S. 2191 and H.R. 2454. EPPA, MERGE, and MiniCAM were all used for the Climate Change Science Program Synthesis and Assessment Product 2.1a (Clarke et al., 2007), which presented scenarios of greenhouse gas emissions and atmospheric concentrations. The MERGE and MiniCAM models have also been used for the international transition scenarios portion of this EMF 22 study.

2.2. Scenario design

The U.S. transition scenarios portion of the EMF 22 study is built around three common scenarios run by all of the modeling teams that have their origin in an analysis conducted to capture a wide range of policy alternatives (see, Paltsev et al., 2008). The scenarios include three linear allowance allocation paths for the period from 2012 to 2050 that all begin at the 2008 emissions level, followed by: (1) a constant annual level through 2050; (2) a path falling to 50% below 1990 levels by 2050; and, (3) a path falling to 80% below 1990 levels by 2050. Fig. 1 shows historic U.S. emissions and compares the range of projected reference scenario emissions from the participating models against the above-specified targets.

The caps are based on CO_2-equivalents, covering all of the Kyoto Protocol gases (CO_2, CH_4, N_2O, and fluorinated gases), and using CO_2-equivalent emissions factors.[1] The emissions caps cover the entire economy's energy-related CO_2 emissions and all non-CO_2 GHGs. They do not cover land use emissions of CO_2 or credit CO_2 sequestration from agriculture and forestry. There are no credits allowed from international emissions trading or from offsets, so all reductions must occur within the U.S. Guidelines on international assumptions for the study are roughly in line with the global delayed participation scenarios from the international transition scenario portion of the EMF 22 study. Since emissions trading is not allowed, the international assumptions likely do not have strong effects on the U.S. results, but what happens abroad can affect the U.S. through international trade.

Table 1
2012-2050 cumulative U.S. GHG emissions ($GtCO_2e$) assuming linear reductions from estimated 2008 emissions levels in 2012 to specified 2050 target and assuming 100% coverage.

	% below base year emissions in 2050						
Base year	*83%*	*80%*	*65%*	*50%*	*35%*	*20%*	*0%*
1990	164	**167**	185	**203**	221	239	262
2005	167	171	192	213	234	254	282
2008	168	172	194	215	237	258	**287**

Note: Numbers in red are scenarios analyzed in the EMF 22 exercise. Emissions data from 1990 and 2005 are based on EPA's 2009, "U.S. inventory of greenhouse gas emissions and sinks" (U.S. EPA, 2009). 2008 emissions projections are based on the MIT report, "Assessment of U.S. cap-and-trade proposals" (MIT, 2007).

The EMF 22 scenarios allow full banking and borrowing, and the emissions pathways can be interpreted as cumulative emissions targets for the period 2012 through 2050: 287 $GtCO_2e$ under the constant emissions scenario; 203 $GtCO_2e$ under the 50% below 1990 levels by 2050 scenario; and 167 $GtCO_2e$ under the 80% below 1990 levels by 2050 scenario. Table 1 shows these cumulative emissions along with the cumulative emissions from a range of percentage reductions for emissions in 2050 below base years of 1990, 2005, and 2008, as various policy proposals have called for different levels of reductions using different base years. This table shows, for example, that a 2050 target of 80% below 1990 level emissions for the U.S. is

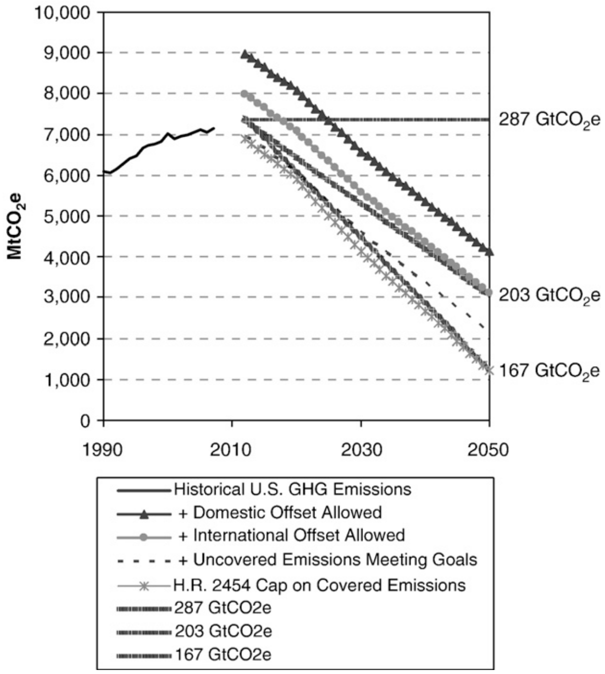

Fig. 2. Comparison to H.R. 2454.

Table 2
H.R. 2454 cumulative emissions.

Cumulative 2012–2050 U.S. GHG emissions ($GtCO_2e$)	
Allowances to covered sectors	131
Plus emissions from uncovered sectors if total U.S. goal is met	159
Plus international offsets allowed	198
Plus domestic offsets allowed	237

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[1] For GHG emissions inventories and mitigation, the common practice is to compare and aggregate emissions by using global warming potentials (GWPs). Emissions are converted to a carbon dioxide equivalent (CO_2e) basis using GWPs as published by the Intergovernmental Panel on Climate Change (IPCC). GWPs used here and elsewhere are calculated over a 100-year period, and vary due to both the gases' ability to trap heat and their atmospheric lifetime compared to an equivalent mass of CO_2. Although the GWPs have been updated by the IPCC in the Fourth Assessment Report (Forster, 2007), estimates of emissions in this report continue to use the GWPs from the Second Assessment Report (Houghton, 1995), in order to be consistent with international reporting standards under the UNFCCC.

Table 3
International transition scenarios—Policy.[3]

	Ref	650	650	550	550	550	550	450	450	450	450
	N/A	Full	Delay	Full	Full	Delay	Delay	Full	Full	Delay	Delay
	N/A	N.T.E	N.T.E.	O.S.	N.T.E.	O.S.	N.T.E.	O.S.	N.T.E.	O.S.	N.T.E.
ETSAP-TIAM	303	302	299	255	251	255	222	144	85	70	
FUND	368	319	294	246	244	185	139	107			
GTEM	318	279	267	245	230	228		190			
IMAGE	427	333	320	292	262	276	195				
MERGE optimistic	296	244	218	202	189						
MESSAGE	306	277	233	277	236	242		258			
MiniCAM-Base	310	276	261	261	238	248		220	127	129	
POLES	277	223	216	190	180	173					
SGM	271	229	222	166	166	143	143				
WITCH	419	346	316	270	217	199	139				

equivalent to a target of 83% below 2005 emissions levels. Note that recent legislative proposals have covered less than 100% of emissions and have allowed domestic and international offsets. Thus, for example, the 80% reduction scenario analyzed here requires much greater domestic reductions and involves higher costs than policy proposals with similar stated emissions targets that allow many offsets and cover less of the economy, all else equal.

2.3. Comparison to proposed legislation

In the 111th Congress, in session as this is written, the American Clean Energy and Security Act of 2009 (H.R. 2454), introduced by Congressmen Waxman and Markey, is the most prominent climate bill, and was passed by the House of Representatives. The scenarios modeled in the EMF 22 exercise were not designed to represent a particular bill, but in this section we compare H.R. 2454 to the EMF 22 scenarios. The Waxman–Markey bill has a stated goal of reducing total U.S. greenhouse gas emissions to 83% below 2005 levels by 2050. The cap-and-trade program, covering an estimated 85% of U.S. GHG emissions, allocates allowances to covered sources on a path that falls to 83% below 2005 emissions by 2050.[2] Allowances to covered sectors over the period total 131 $GtCO_2e$. If the economy-wide goal was met and the cap sectors did not use outside credits, cumulative U.S. emissions would be 159 $GtCO_2e$. The bill includes additional policies beyond the cap-and-trade program designed to reduce non-covered emissions in order to achieve the overall stated GHG emissions goals, and it includes other measures directed at covered sectors, and it allows substantial outside offset credits. To compare the partial coverage of the economy in H.R. 2454, we make assumptions about non-covered sectors, adding to the cap-and-trade allowance path, assumed emissions from these sources, and different assumptions about the use of offset credits. In Fig. 2, the path labeled “H.R. 2454 Cap on Covered Emissions” shows the cap as specified in the bill. The three paths labeled with a “+” sequentially add to the cap assumed uncovered emissions that meet the overall emissions goals of the bill, additional U.S. emissions that would be allowed through the use of international offsets, and additional U.S. emissions that would be allowed through the use of domestic offsets (e.g. agriculture and forestry related sinks). Table 2 shows the cumulative emissions for H.R. 2454 under these different assumptions for comparison to the cumulative emissions in the EMF 22 scenarios. While H.R. 2454 has an overall target similar to the EMF 22 167 $GtCO_2e$ allowance target, the domestic reductions from H.R. 2454 would only be similar to this target if the non-capped sources achieve the reduction goals in the bill and no outside offsets credits are used. If offset credits are used, or if the goals for reducing non-covered emissions are not met, then cumulative emissions under H.R. 2454 may be between the 203 $GtCO_2e$ and 287 $GtCO_2e$ EMF 22 targets.

2.4. Comparison to EMF 22 international transition scenarios

It is also useful to relate the U.S. scenarios investigated here to the EMF 22 international transitions scenarios as in Table 3. This table shows cumulative 2012–2050 emissions in the U.S. from each model. The EMF 22 international transition scenarios limited CO_2-equivalent concentrations to 450, 550, and 650 ppm with and without overshoot, under full and delayed participation cases (see Clarke et al., 2009-this volume). From Table 3, we see that the 650 CO_2-e not-to-exceed scenarios with full participation are similar to the 287 $GtCO_2e$ scenario; the emissions reduction required by the U.S.A. in the international models to stabilize CO_2-equivalent concentrations at 650 ppm ranges from 223 $GtCO_2e$ to 346 $GtCO_2e$ scenario in this study. The 203 $GtCO_2e$ scenario requires emissions reductions similar to the 550 ppm overshoot scenario with full participation scenario; cumulative emissions in this scenario range from 166 $GtCO_2e$ to 292 $GtCO_2e$. The 167 $GtCO_2e$ scenario has emissions reductions that are consistent with limiting CO_2-equivalent concentrations to 550 ppm, without overshoot, but with delayed participation, or limiting CO_2-equivalent concentrations to 450 ppm, with overshoot and full participation. Cumulative emissions in the former scenario range from 139 to 222 $GtCO_2e$; cumulative emissions in the latter range from 107 to 258 $GtCO_2e$.

2.5. Limitations of this study

It is important to note some of the limitations of this study. First, while six prominent modeling teams were able to participate in this study, there are other important models that were not able to participate. Most notably, this study does not include a modeling team using the National Energy Modeling System (NEMS), which has been used by the Energy Information Administration for analyses of proposed U.S. climate legislation. Another important limitation of this study is that only three policy scenarios were required from each modeling team. While these scenarios span a wide range of emissions targets, many uncertainties have yet to be explored, and implementation details, such as permit allocation, offsets, cost containment mechanisms, and revenue recycling issues, were not addressed in the

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[2] Because of issues surrounding measuring and monitoring emissions, it is not feasible for a cap-and-trade system to cover 100% of GHG emissions. In this study, we make the simplifying assumption of 100% coverage, so that the emissions targets comport with overall emissions reduction goals. Modeling the cap-and-trade system to cover emissions that might not be covered under an actual policy acts as a proxy for the non cap-and-trade policies that would be needed to reach the overall reduction goals. These non cap-and-trade policies for uncovered sources would generally be less efficient than a price-based cap-and-trade policy.

[3] EMF only collected global F-gas emissions. We have scaled these emissions assuming that the United States maintains a constant fraction of global emissions over time. Additionally, the MESSAGE model includes Canada with the United States. We have scaled the cumulative emissions from this model to represent the U.S. only.

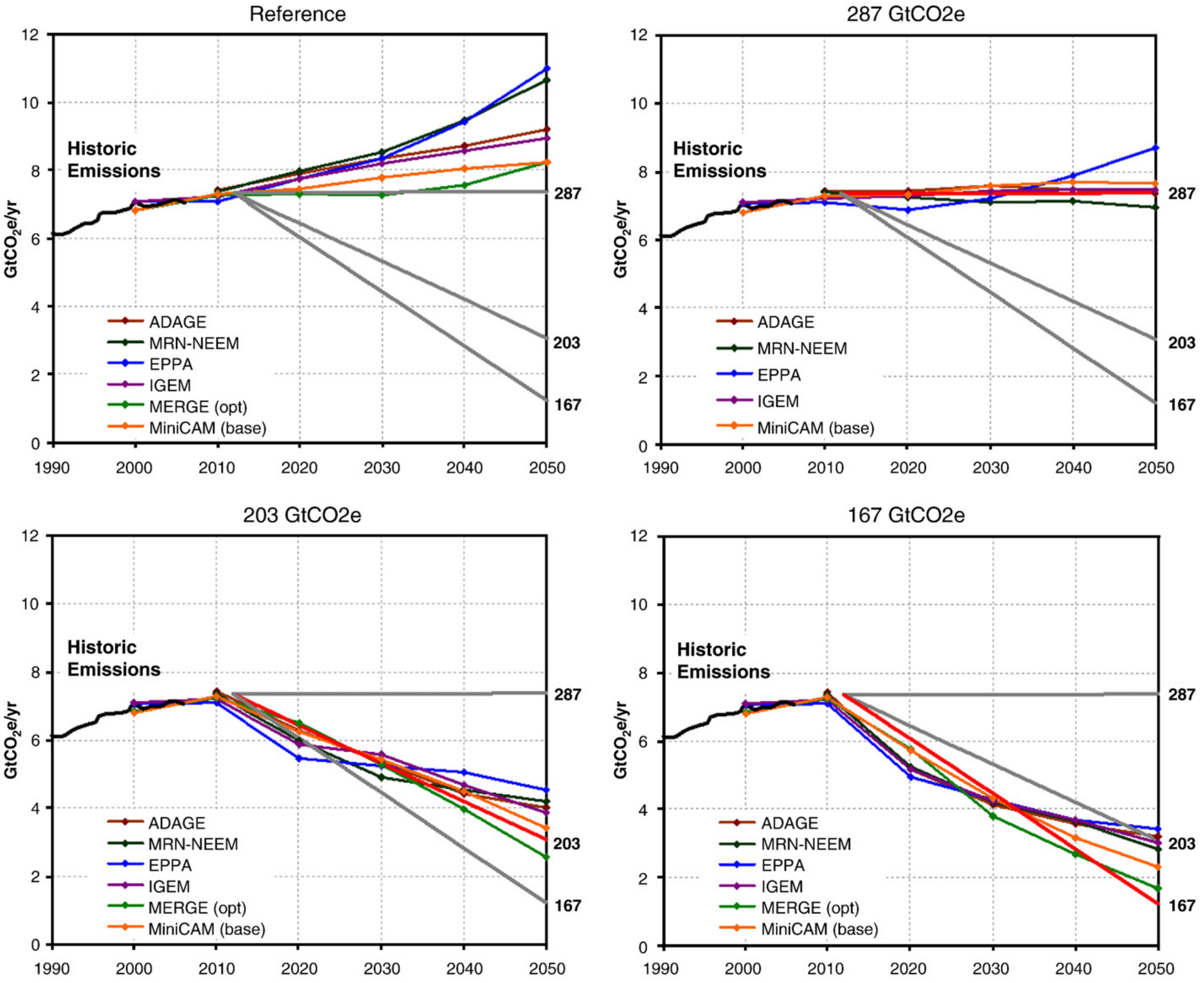

Fig. 3. Emissions pathways.

comparisons. Some, but not all, of these additional uncertainties and details have been addressed by the modeling teams in their individual papers. The remaining issues not covered provide many possible directions for future research. Despite the various limitations and uncertainties, many powerful insights emerged from this study.

3. Emissions pathways

As discussed previously, actual emissions paths will diverge from the allowance allocation paths because of banking and borrowing. Fig. 3 shows total U.S. GHG emissions in the reference and three policy scenarios for each model.[4] The reference case emissions pathways show a wide range of emissions projections across the models, which is likely an important factor in explaining differences in costs among the participating models. Differing levels of emissions in the reference case imply different amounts of abatement required to meet the caps established in the three policy scenarios. The difference in 2012–2050 cumulative GHG emissions between the highest reference emissions (MRN–NEEM) and the lowest reference emissions (MERGE) is approximately 50 GtCO$_2$e. As a result, the amount of abatement required for MRN–NEEM to reach the 203 GtCO$_2$e target is 50% greater than the amount of abatement required by MERGE.

The emissions pathways in the three policy scenarios are far more similar across all of the models than the pathways in the reference case, as all of the models face the same cumulative emissions targets. Differences arise because of allocation of allowances across time under the banking and borrowing assumption. Focusing on the 167 GtCO$_2$e scenario, all of the models show emissions levels below the cap level in the early years as they build up a bank of allowances, and emissions levels above the cap level in later years as the bank of allowances is drawn down. The 2050 annual GHG emissions levels differ by as much as 1.75 GtCO$_2$e. The differences in the banking behavior are driven by five factors. The main factor driving banking is the allowances distributed in each period compared with the reference emissions in the period. The allowance paths are generally “front-loaded”; that is they decline over time or are constant while reference emissions rise. Other things equal, that will tend to favor banking. A second factor is the cost, for a given level of abatement, over time, and this can work in either direction. If new low-GHG technologies only became available in later periods or their costs fall, this would favor borrowing, tending to offset the front-loading of

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[4] In the individual papers, many modelers discuss more than one variation of their models. This paper, however, includes only one variation per model. Thus, for purposes of this paper, any mention of “MERGE” refers to the optimistic economic growth version; “MiniCAM” refers to the base technological assumption version.

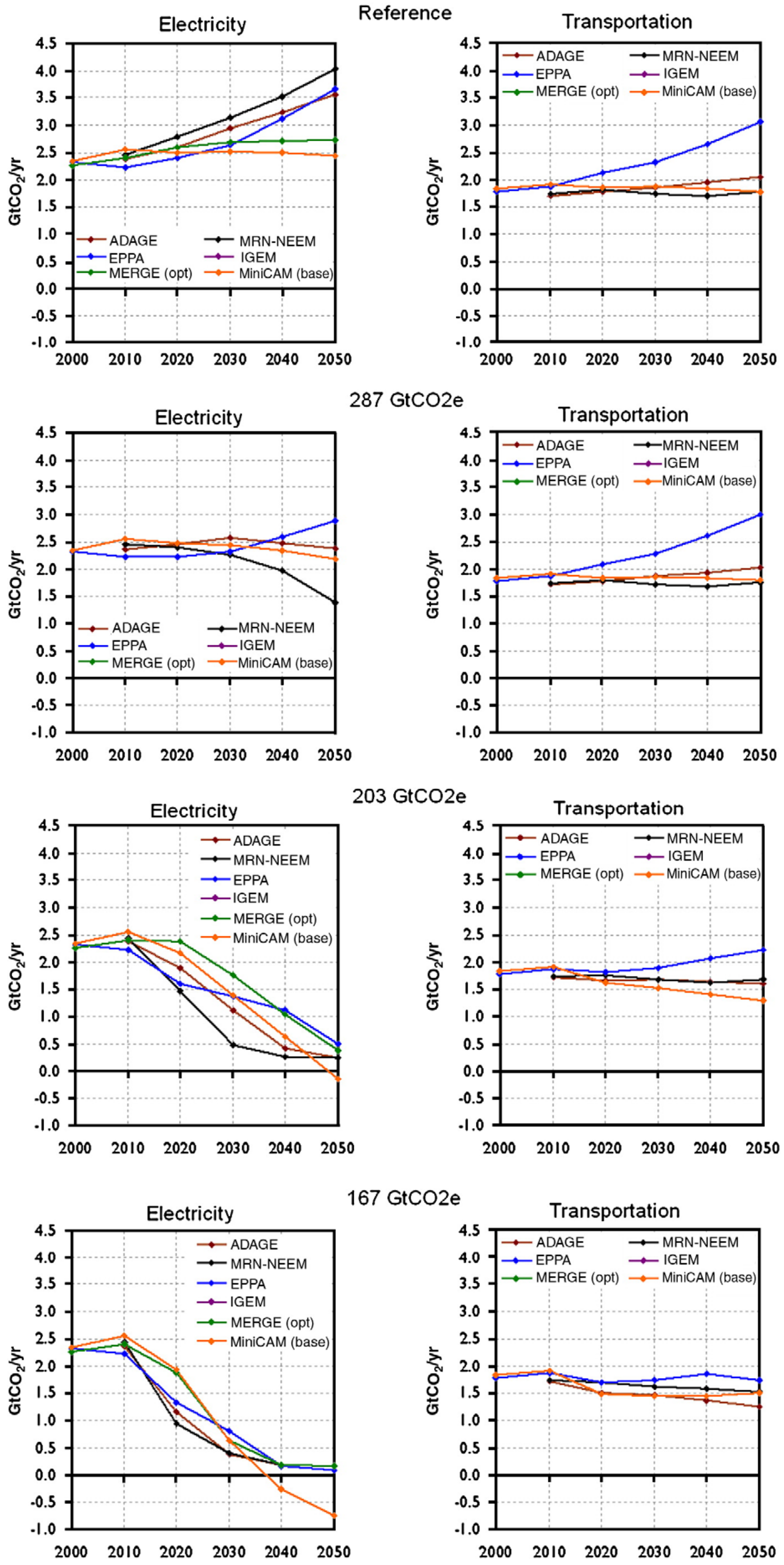

Fig. 4. Electricity and transportation CO_2 emissions.

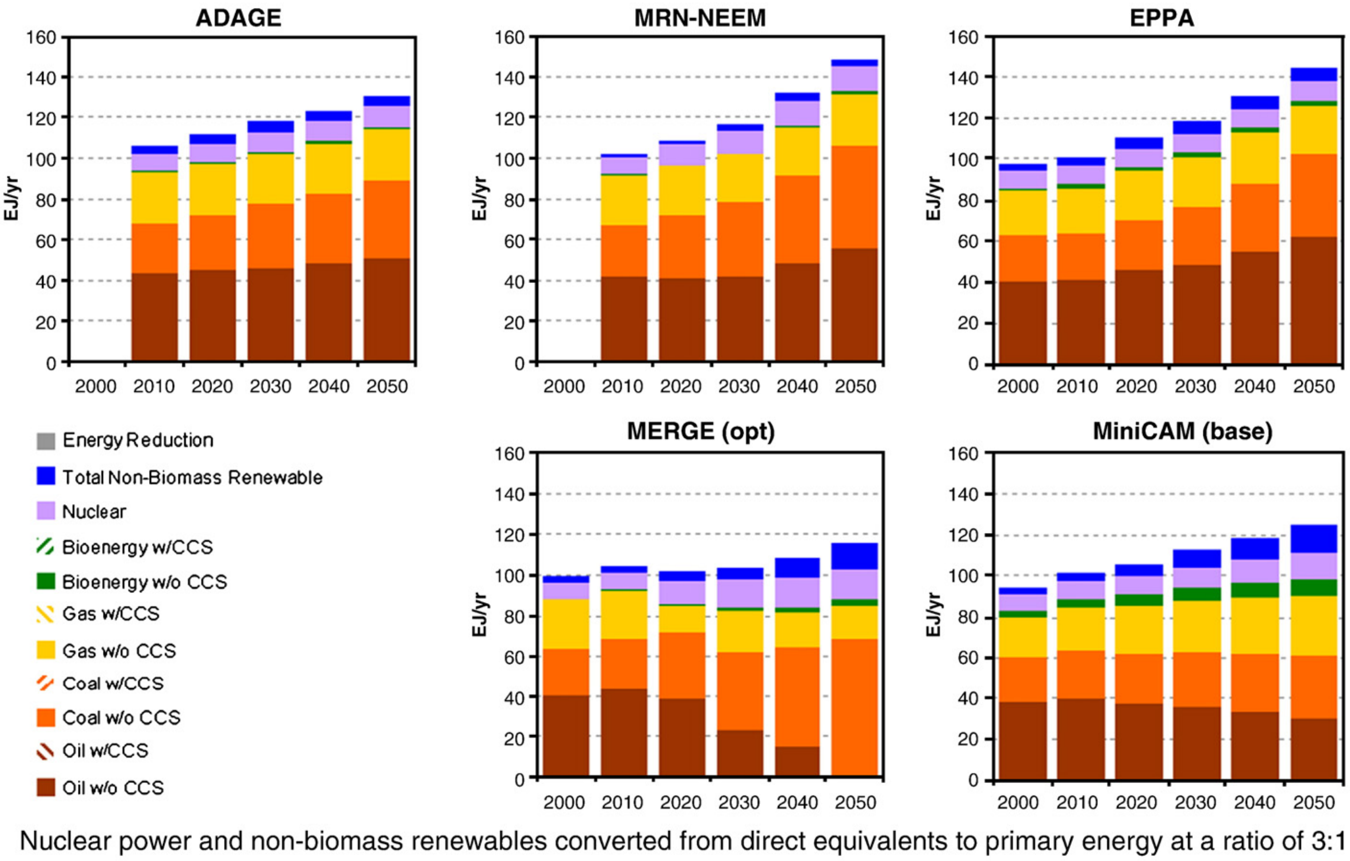

Fig. 5. Primary energy: reference.

allowance allocation. Increasing costs of fossil fuels in the long-term because of resource depletion would also reduce the relative cost of switching to technologies that do not use fossil fuels, again favoring more abatement later. On the other hand, if renewables or other low-GHG technologies face an upward sloping supply curve, their costs could rise as they are more widely deployed, thereby favoring banking. The third factor affecting banking behavior is the rate at which capital stock can be replaced. Models with limited ability to replace existing capital have higher-cost near-term abatement, thus favoring delaying abatement until later periods. The fourth factor is the interest rate used for banking.[5] A relatively low interest rate means that *ceteris paribus* the allowance price will start relatively higher, grow at a slower rate, and end relatively lower. This will lead to more abatement early on, a greater amount of banking, and less abatement in the later years.[6] The final factor leading to different banking pathways is the combination of foresight in the model and the assumption about post-2050 policy. MERGE, IGEM, ADAGE, and MRN–NEEM are all intertemporally optimizing models with perfect foresight. MERGE runs through 2100 and thus makes explicit assumptions about policy post-2050 which have an influence on prices in the first part of the century and the incentives to bank or borrow. IGEM, ADAGE, and MRN–NEEM only model through 2050, but make implicit assumptions about post-2050 policy through the models' terminal conditions; these assumptions will influence the incentive to bank or borrow. If the assumed post-2050 policy is stringent, decision-makers will want low emissions in 2050, thus reducing their incentives to bank reductions early in the century. MiniCAM and EPPA are recursive dynamic and assume the bank of allowances in 2050 is zero. Thus, assumptions about post-2050 policy have no impact on the emissions pathway or costs through 2050.

Fig. 4 shows annual CO_2 emissions from the electricity and transportation sectors in the reference case and under the three policy scenarios. In 2000, electricity sector CO_2 emissions are slightly higher than transportation sector CO_2 emissions (~2.3 $GtCO_2$ from electricity and ~1.8 $GtCO_2$ from transportation), and by 2050 in the reference scenario, the range of CO_2 emissions projected by the models is still slightly higher for electricity than for transportation (2.5–4.0 $GtCO_2$ from electricity and 1.8–3.0 $GtCO_2$ from transportation). In scenarios with national emissions targets, however, all of the models show that the electricity sector reduces emissions more than the transportation sector. In the 287 $GtCO_2e$ scenario, electricity sector emissions across all of the models are reduced by between 11% and 65% below the reference case, while transportation sector emissions range from 2% below reference levels to 1% above reference levels. For the 203 and 167 $GtCO_2e$ scenarios, electricity sector emissions are reduced by 86% to 106% and 94% to 130% in 2050, respectively; and transportation sector emissions fall by 5% to 27% and 14% to 43% respectively. Emissions reductions larger than 100% below reference levels are due to the inclusion of biomass combined with CCS and imply negative emissions from the electricity sector. These negative emissions include the CO_2 emissions uptake occurring in the terrestrial system.

If we consider the stated emissions reduction goals for 2050 in the policy scenarios (e.g. 80% below 1990 levels by 2050 for the

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[5] Under banking, holders of allowances will compare the expected net present value of allowances in the near-term and long-term as they do with other investments. A higher rate of interest will make allowances in the future less expensive in net present value terms and favor less banking than if the interest rate is lower. Allowances over time are fixed by the policy, and an economic theory result demonstrates that economic efficiency is achieved if such an asset is allocated over time such that the net present value price of allowances remains constant over time (the undiscounted price will rise at the interest rate; Peck and Wan 1996).

[6] Most of the models in this study have a 5% interest rate for banking, the EPPA model has a value of 4%, and the MERGE model has a value of 4.35%.

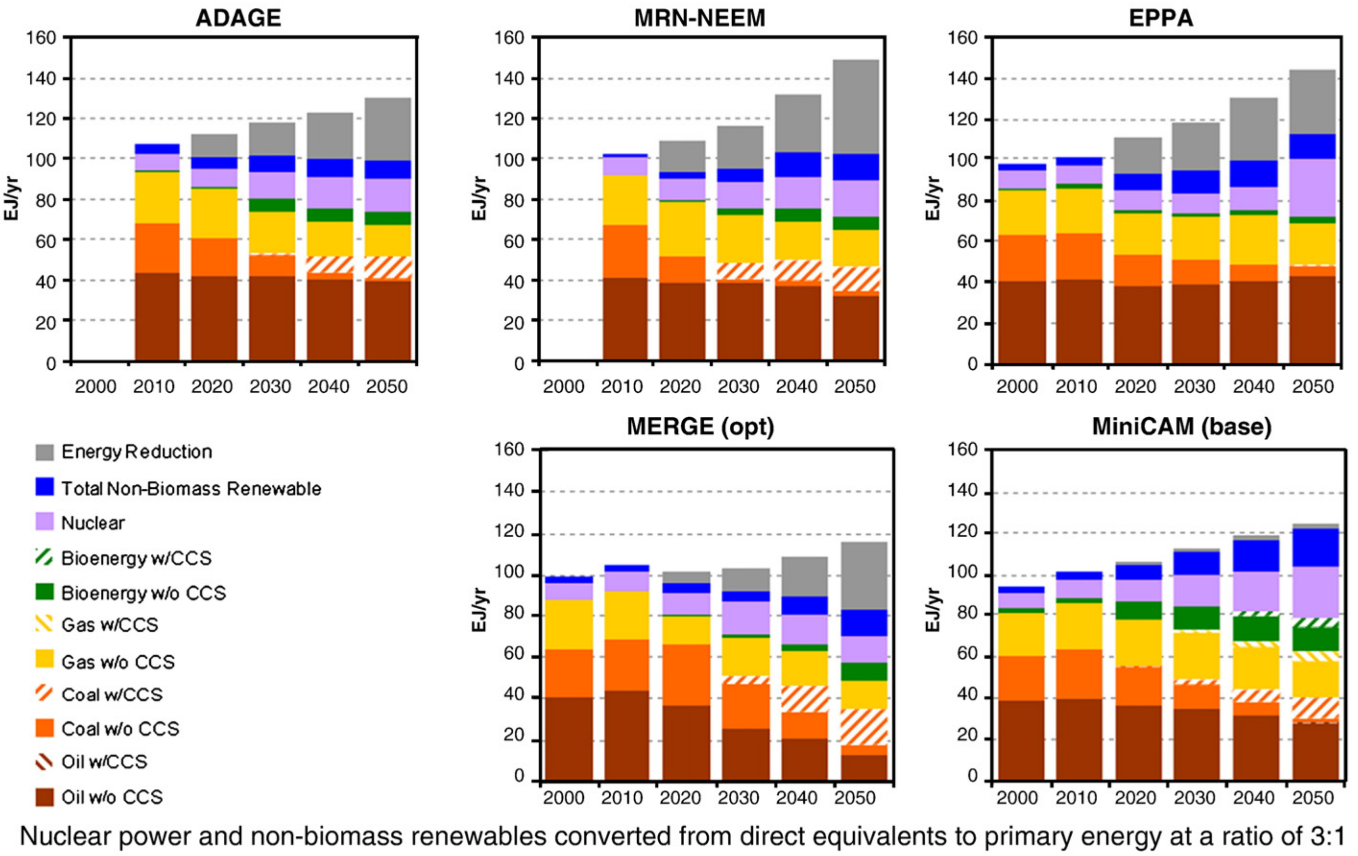

Fig. 6. Primary energy: 203 $GtCO_2e$.

167 $GtCO_2e$ scenario), the electricity sector reduces emissions to levels well below the targets, while the transportation sector emissions remain well above the targets. This is an important feature of the cap-and-trade system. Sectors are not all forced to reach the same targets; instead, the emissions reductions occur where they are least expensive to achieve, and the cost of the last ton of emissions reduced in the electricity sector is equal to the cost of the last ton of emissions reduced in the transportation sector.

4. Primary energy and electricity generation

The imposition of a climate policy changes the energy system substantially. In this section, we look at the effect of policy on the consumption of primary energy and the generation of electricity. Here we focus on a comparison of the reference and 203 $GtCO_2e$ scenarios.

4.1. Primary energy

Fig. 5 shows primary energy in the reference scenario across all six participating models. Growth in primary energy over the next 50 years varies across the models, with energy consumption in 2050 ranging from a low in MERGE of 115 EJ/yr to a high in MRN–NEEM of 150 EJ/yr.[7] All models show a continued dependence on fossil fuels throughout the time horizon, with MERGE switching to a predominantly coal-based economy, while the other five models continue to use a balance of coal, gas, and oil. Despite this dependence, growth in the consumption of non-biomass renewables is significant, doubling between 2000 and 2050 in one of the models (EPPA) and quadrupling in two of the models (MERGE and MiniCAM).

Fig. 6 shows the primary energy results for the 203 $GtCO_2e$ scenario. Under this policy scenario, all six models show reductions in primary energy from the reference scenario. In one model (MiniCAM), the reduction in energy consumption is small, representing less than 2% of reference energy consumption in all periods. The other models show a more substantial reduction, ranging in 2050 from 22% of reference energy in EPPA to 32% of reference energy in MRN–NEEM.

These reductions in energy capture both efficiency improvements and reductions in energy services. The degree to which a model exhibits a reduction in energy use depends on its technology availability and consumer response in terms of willingness to reduce energy-consuming activities. The inclusion of more advanced end-use technologies in particular can result in reduced energy consumption, as consumers switch to more efficient technologies to meet the same level of service.

Imposing a climate policy changes not only total primary energy consumption, but also the energy supply mix. All of the five models that include nuclear energy, bioenergy, and non-biomass renewables show increased use of these fuels under a policy. All of the models include CO_2 capture and storage as a means of reducing the emissions associated with fossil fuels, but the degree to which it is used varies widely. In the EPPA model it enters only in the final period at a very low level. In other models, it enters as early as 2030. Low-carbon sources (fossil fuels with CCS, bioenergy, nuclear, and non-biomass renewables) account for between 39% (EPPA) and 62% (MERGE) of total primary energy supply in 2050 in the 203 $GtCO_2e$ scenario. In contrast, these technologies accounted for between 12% (ADAGE, MRN–NEEM) and 28% (MiniCAM) of total primary energy supply in 2050 in the reference scenario.

4.2. Electricity generation

Fig. 7 shows electricity generation in the reference scenario. All five models that report electricity generation show an increase in electricity

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[7] Note that IGEM only reports fossil fuel consumption and not nuclear or renewable energy.

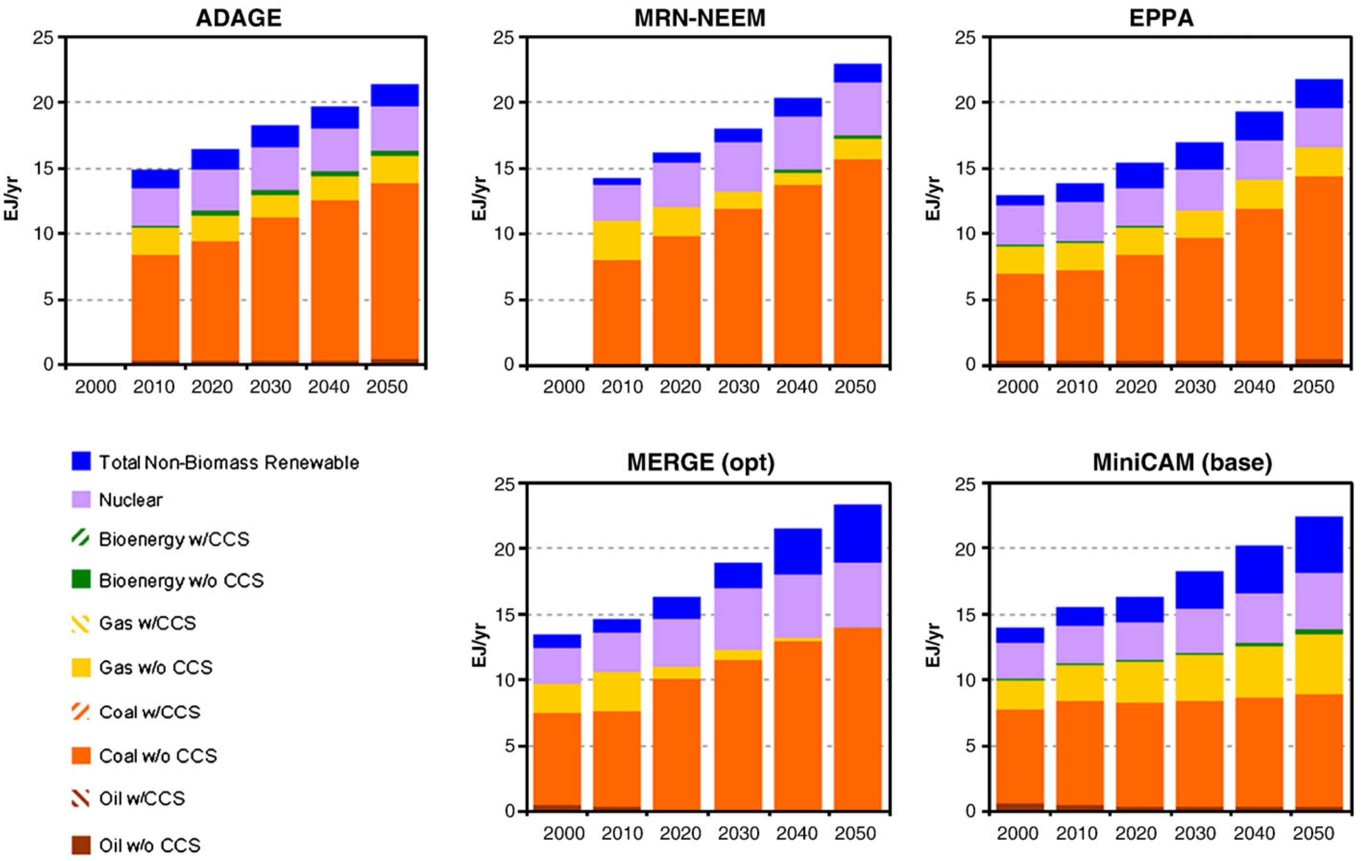

Fig. 7. Electricity generation: reference.

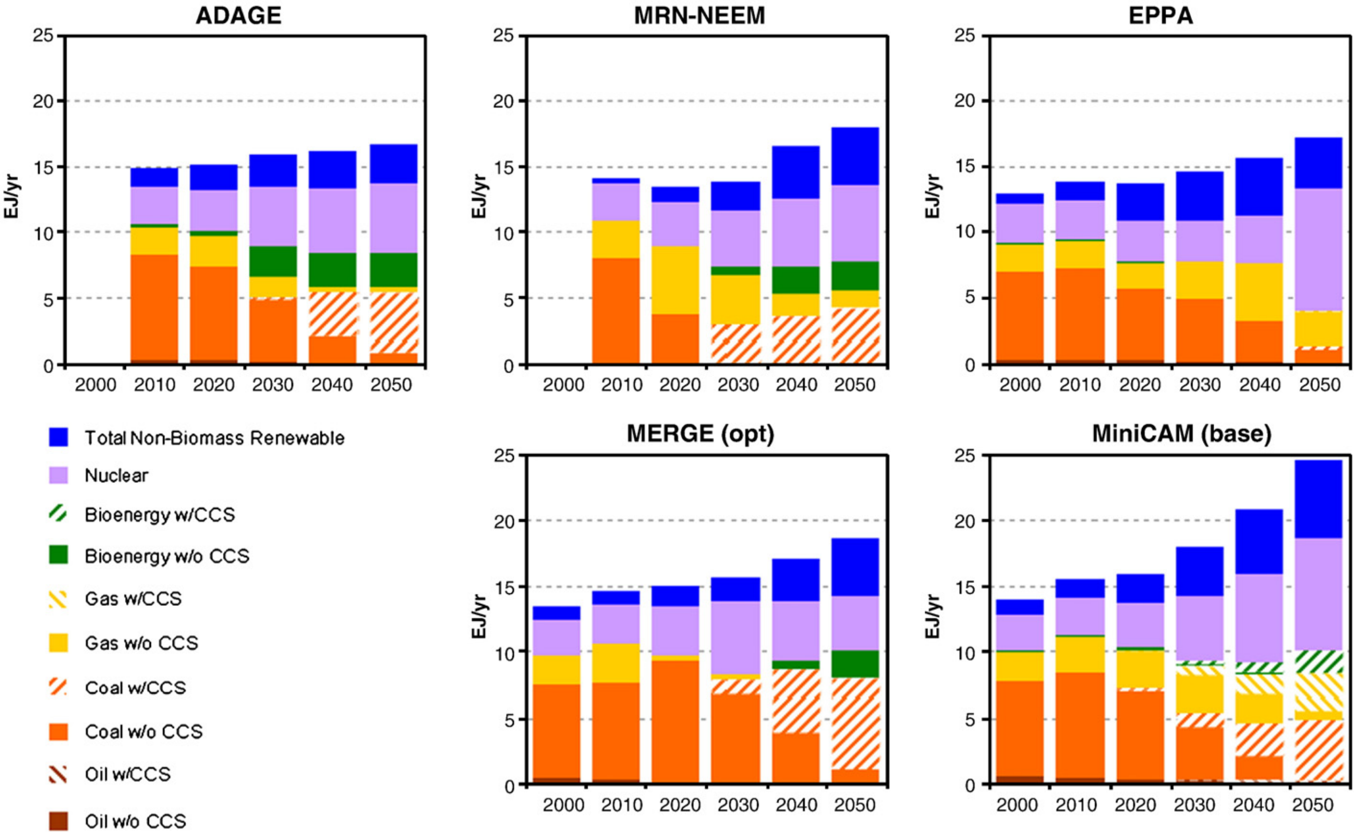

Fig. 8. Electricity generation: 203 $GtCO_2e$.

generation from approximately 13 EJ/yr in 2000 to between 21 and 23 EJ/yr in 2050. While all models are relatively consistent in estimates of total electricity, there is some variation in their projected generation mixes. Three of the models (ADAGE, EPPA, and MRN–NEEM) show increases in the shares of coal and renewable generation, and decreases in the shares of gas and nuclear generation. Another model (MiniCAM) shows a relatively constant share of nuclear generation, increases in the shares of generation from gas and renewables, and a declining share of coal generation. All models exhibit continued dependence on electricity generation from fossil fuels in the reference scenario.

Fig. 8 shows electricity generation in the 203 $GtCO_2e$ scenario. Under a carbon policy, all models show a significant shift toward low-carbon generation technologies. By 2050, between 79% (EPPA) and 97% (MiniCAM) of all electricity generation is from low-carbon technologies; compared to 24% to 40% of total primary energy from low-carbon sources. This is consistent with the result that reduction in emissions from the electricity sector is greater than the reduction in economy-wide emissions. While all models shift to low-carbon technologies, different models rely more heavily on different technologies. For example, MiniCAM and MERGE show large deployment of CCS, while EPPA depends more on nuclear power.

5. Economic implications of meeting emissions goals

In this study we focus on two types of economic impacts: allowance prices and aggregate economic consumption impacts. The allowance price is a measure of the marginal cost of abating GHG emissions. The consumption impact is a measure of the change in consumption of goods and services in the economy, one measure of the aggregate economic cost. It measures how much less goods and services households can purchase given the rises in energy prices and other costs resulting from GHG abatement. Section 5.1 presents the allowance price results. Section 5.2 discusses the consumption impact results.

5.1. Allowance prices

Allowance prices vary across the three policy scenarios and six participating models. Fig. 9 depicts allowance prices in each of the three scenarios, with the 287 $GtCO_2e$ scenario depicted twice, once with a scale that allows comparison across models, and once with a scale that allows comparison across scenarios. While allowance prices in ADAGE, IGEM, and EPPA are similar in the 287 $GtCO_2e$ scenario, MRN–NEEM and MiniCAM exhibit considerably different prices.

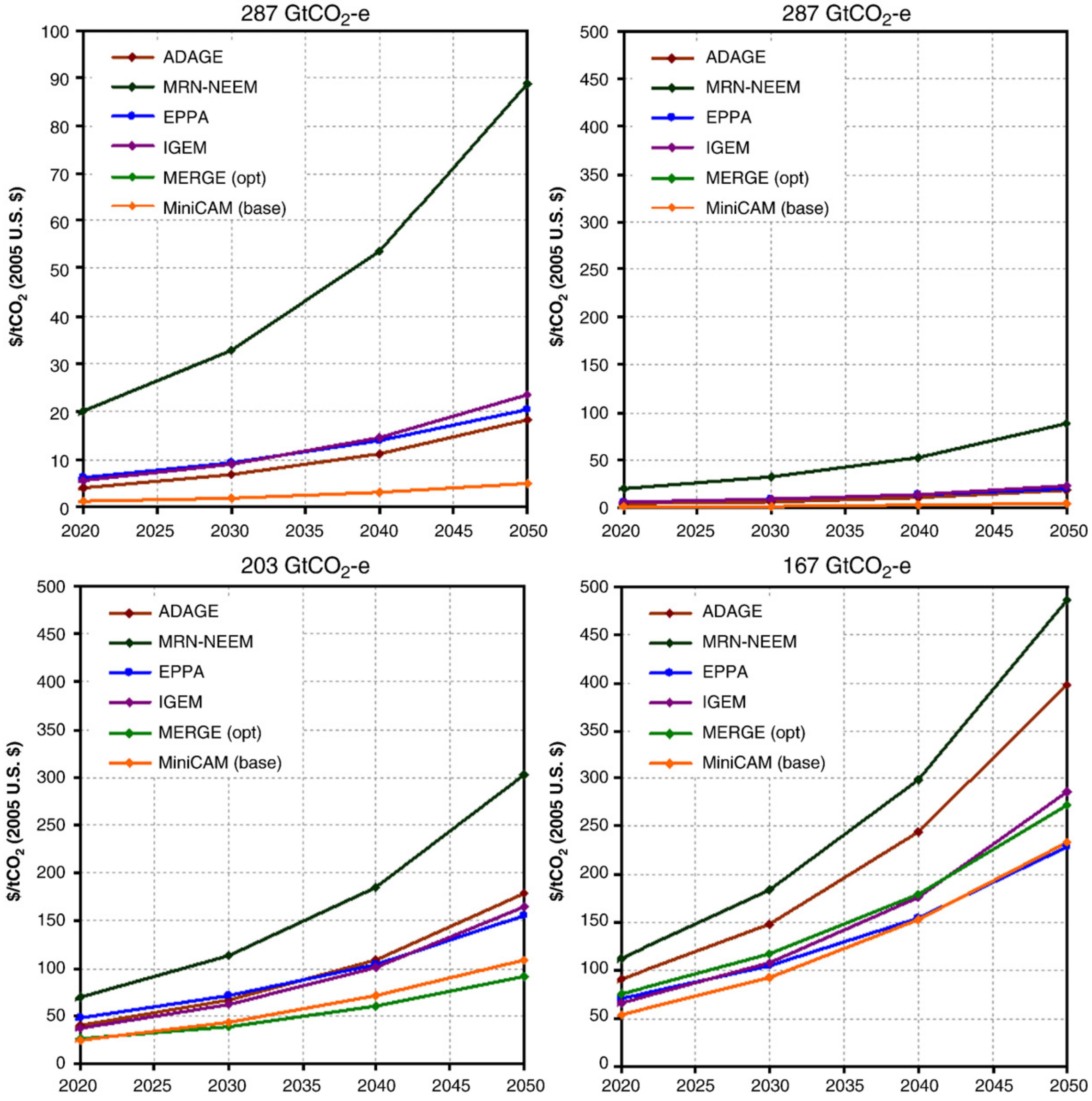

Fig. 9. Allowance prices.

ADAGE, IGEM, and EPPA all have allowance prices between 4$/$tCO_2$e and $6/$tCO_2$e in 2020; these prices grow to between $18/$tCO_2$e and $24/$tCO_2$e in 2050. MiniCAM has the lowest allowance price, starting at $1/$tCO_2$e in 2020 and growing to $5/$tCO_2$e in 2050. MRN–NEEM has the highest allowance price, beginning at $20/$tCO_2$e in 2020 and growing to $89/$tCO_2$e in 2050. The 287 $GtCO_2$e target is non-binding in MERGE due to assumptions about post-2050 policy, so the allowance price is zero.

Like the 287 $GtCO_2$e scenario, the 203 $GtCO_2$e scenario allowance prices for ADAGE, IGEM, and EPPA lie somewhere in between the relatively high prices from MRN–NEEM and low prices from MERGE and MiniCAM. 2020 allowance prices for ADAGE, IGEM, and EPPA range from $38/$tCO_2$e in IGEM to $48/$tCO_2$e in EPPA. MiniCAM and MERGE show lower allowances prices, both close to $25/$tCO_2$e in 2020; and MRN–NEEM shows a higher allowance price of $70/$tCO_2$e in 2020. By 2050 the range across all of the models is $92/$tCO_2$e in MiniCAM to $303/$tCO_2$e in MRN–NEEM.

The 167 $GtCO_2$e scenario presents a somewhat different distribution of allowance prices across models. In 2020, allowance prices in MiniCAM, MERGE, IGEM, and EPPA all fall between $54 and $76/$tCO_2$e with MiniCAM at the low end and MERGE at the high end. ADAGE has a somewhat higher allowance price of $91/$tCO_2$e, and MRN–NEEM is higher yet at $113/$tCO_2$e. By 2050, the ordering is somewhat different due to the differing growth rates of the allowance prices. MiniCAM and EPPA are at the low end of the range with allowance prices of $234 and $229/$tCO_2$e, respectively, and allowance prices in MERGE and IGEM are slightly higher at $273 and $286/$tCO_2$e, respectively. The ADAGE allowance price is considerably higher at $398/$tCO_2$e, and MRN–NEEM has the highest allowance price at $487/$tCO_2$e. Thus, like the 203 $GtCO_2$e and 287 $GtCO_2$e scenarios, MiniCAM exhibits one of the lowest allowance prices, while MRN–NEEM reports the highest allowance price. However, the relative ordering of the remaining four models differs in this scenario from the other two scenarios.

Several factors lead to differences in allowance prices across models. The first major driver of differing cost estimates is differences in the amount of GHG emissions in the baseline. A model with higher reference case GHG emissions simply has to abate more to reach any given emissions target. The second major driver of differing cost estimates is technology, or the substitution possibilities available in the models. Higher capital costs for nuclear and CCS, or restrictions on the penetration rates of these technologies, would both tend to lead to higher allowance prices. Next, the flexibility of the capital stock will influence how quickly old technologies can be phased out and new technologies can be adopted. Finally, assumptions about post-2050 policy in an intertemporally optimizing model can have implications on allowance prices. If the post-2050 policy requires substantial emissions reductions, then decision-makers may undertake emissions abatement earlier in the century in anticipation of this policy.

To help understand the differences in allowance prices across the models, Fig. 10 plots for each scenario and each model the amount of abatement achieved against the allowance price, or marginal cost of abatement, in each year. These plots represent a marginal abatement cost (MAC) curve for each model. The MAC curves allow us to isolate the impact of differences in the baseline scenario on allowance prices from the impact of other factors on allowance prices.

Previously, we noted that MRN–NEEM consistently had the highest allowance price, while MiniCAM had one of the lowest. We can use the MAC curves to understand both effects. In the 203 $GtCO_2$e scenario, MERGE and MiniCAM had the lowest allowance price in 2050 at $92/$tCO_2$e and $109/$tCO_2$e, respectively, while MRN–NEEM at $302/$tCO_2$e had the highest allowance price. However, the three models achieved vastly different amounts of abatement in this

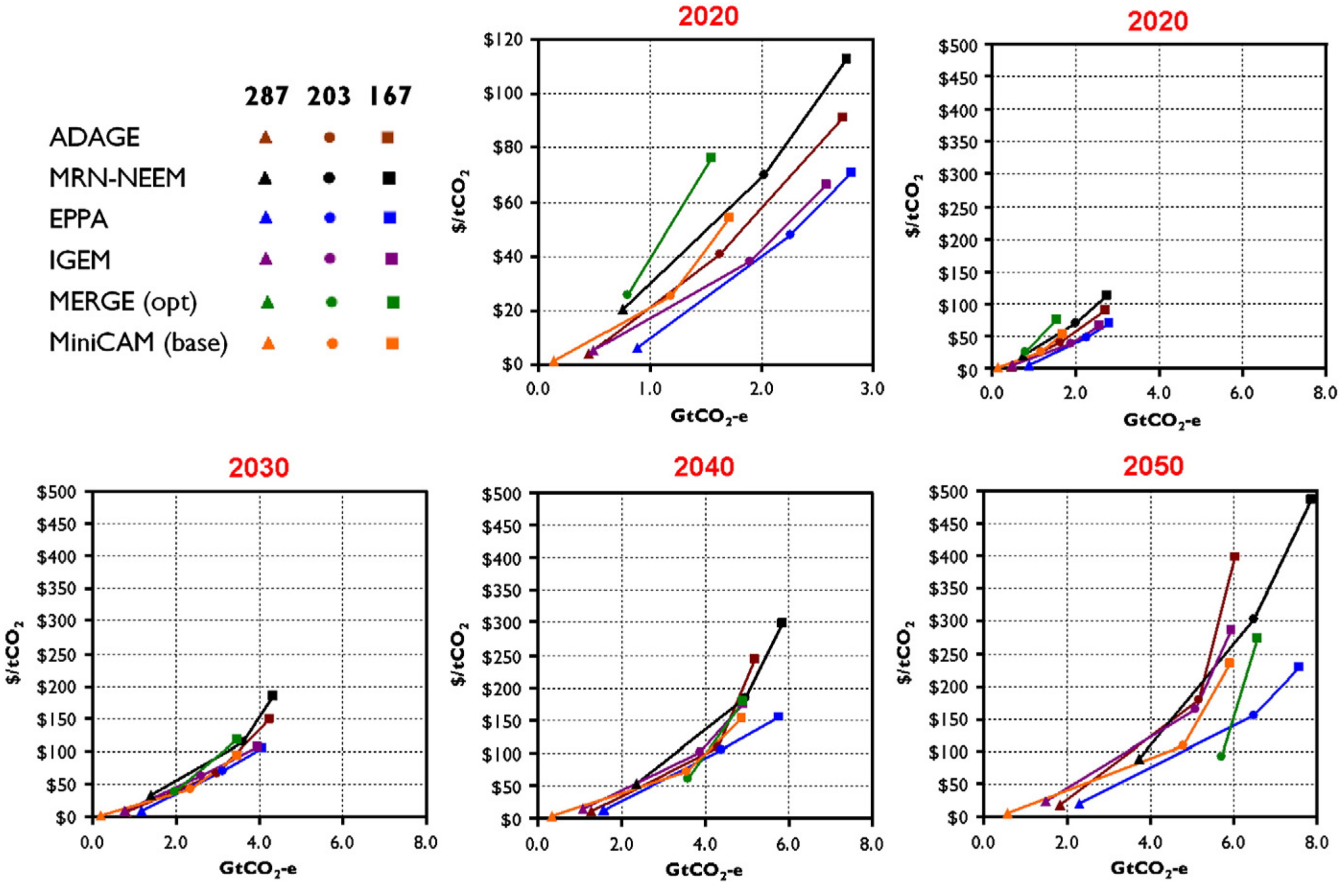

Fig. 10. Marginal abatement cost curves.

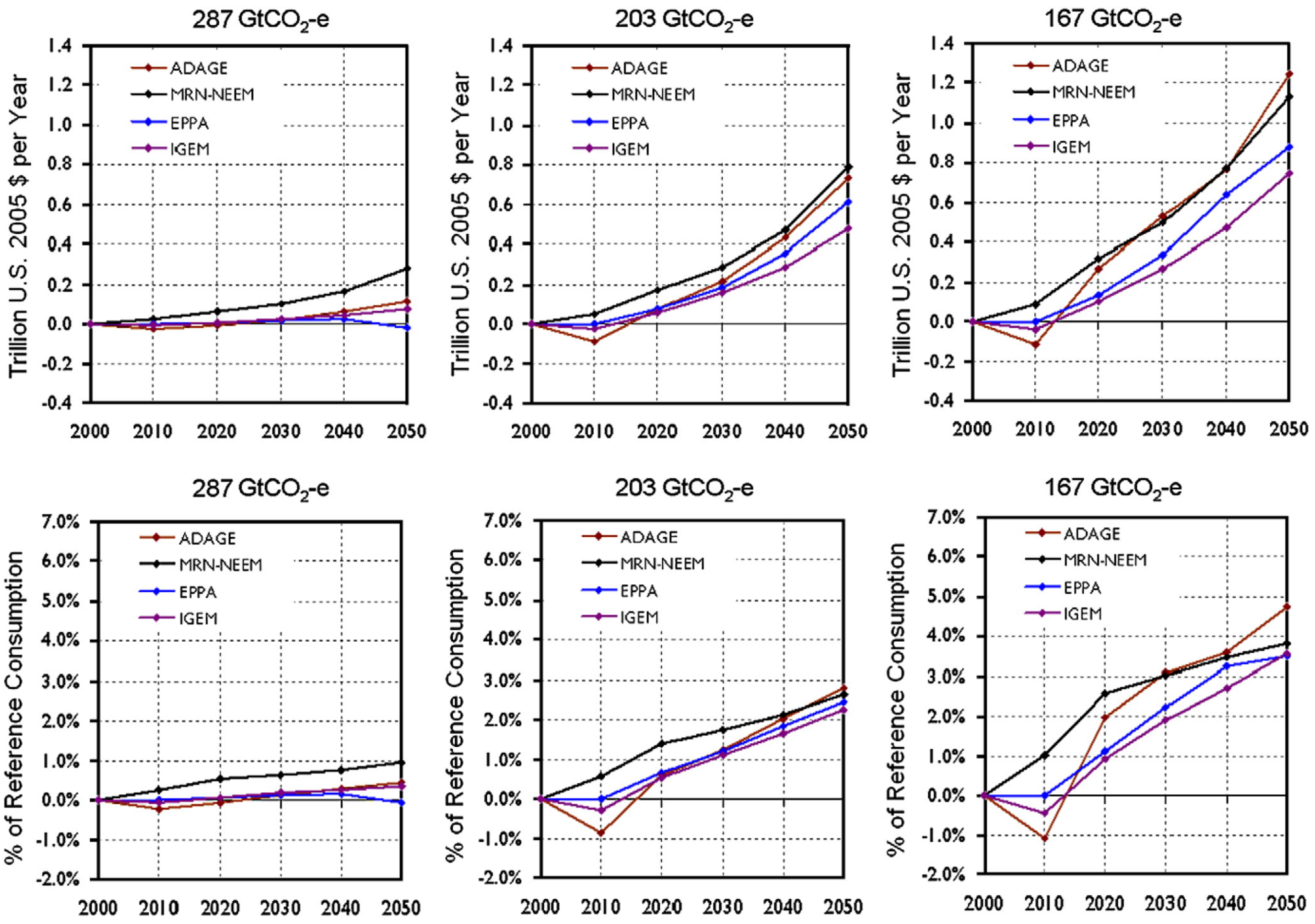

Fig. 11. U.S. consumption impacts.

scenario. MiniCAM only needed 4.8 $GtCO_2e$ per year of abatement in 2050 in the 203 $GtCO_2e$ scenario, the lowest requirement of any model. MRN–NEEM needed 6.5 $GtCO_2e$ per year in 2050 in the same scenario, the highest requirement of any model. MERGE's abatement requirements fall somewhere in the middle at 5.7 $GtCO_2e$ per year. The large level of abatement required by MRN–NEEM is one contributing factor to its high allowance price.

How the MAC curves evolve over time for each model is an indication of the flexibility of the capital stock and the degree of assumed future technological advance. Looking at how much abatement is achieved according to the MAC curves for a \$50/tCO_2e allowance price in each year, we see some interesting results. The MAC curve for IGEM does not shift out over time; at \$50/tCO_2e IGEM generates 2.2 $GtCO_2e$ of abatement in 2020 or 2050. In MERGE on the other hand, at \$50/tCO_2e the model generates 1.2 $GtCO_2e$ of abatement in 2020 and 3.1 $GtCO_2e$ of abatement in 2050.[8]

The MAC curves presented here for each year are limited to the three data points corresponding to the three scenarios in this exercise. Even so, they are still useful tools for understanding the responsiveness of the models. With three points in the MACs we can still see generally how the slope of the MACs changes on either side of the point for the 203 $GtCO_2e$ scenario. In 2050, the MAC curve for ADAGE shows that the 203 $GtCO_2e$ point represents a knee in the MAC curve as the allowance price is considerably higher for the 167 $GtCO_2e$ scenario without much more abatement. In MiniCAM on the other hand the bend in the knee is much shallower. MERGE shows a slope between the 203 and 167 $GtCO_2e$ scenarios similar to ADAGE, but shifted out and down, showing that more abatement is available at a lower price before reaching a similar knee in the MAC curve.

5.2. Consumption

Four of the six models participating in the U.S. transition scenarios portion of EMF 22 reported consumption impacts (Fig. 11). In the 287 $GtCO_2e$ scenario, the MRN–NEEM model showed a 0.5% (\$66 billion) decrease in consumption in 2020, while ADAGE, EPPA, and IGEM all had consumption impacts of 0.1% (\$9 billion) or less. In 2050, the MRN–NEEM consumption loss had increased to 0.9% (\$283 billion), IGEM and ADAGE reported consumption losses of 0.4% (\$77 and \$115 billion respectively),[9] and EPPA actually experienced a small 0.1% (\$18 billion) increase in consumption due to terms of trade effects from policies implemented abroad.

A clearer pattern of consumption impacts emerges in the 203 $GtCO_2e$ scenario. The ADAGE and IGEM models both show consumption increases in 2010. In both of these models consumers face an intertemporal optimization decision of how to allocate consumption across time. Consumers are aware that the policy will

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[8] These calculations assume a \$0/tCO2e allowance price and 0 $GtCO_2e$ of abatement for the non-binding 287 $GtCO_2e$ scenario in MERGE, although this point is not explicitly shown in the figure.

[9] For a given level change in consumption, IGEM shows a greater percentage change than the other models, because reference consumption is lower in IGEM. The difference in reference consumption between the models arises from an important accounting distinction. The Jorgenson-IGEM accounts treat consumer durables like housing differently than they are treated in the U.S. National Income Accounts (NIA). Specifically, expenditures on these appear as part of investment, not consumption as in the NIA, while their capital service flows are added to both consumption and GDP. This accounting treatment lowers consumption's share of GDP and raises investment's share of GDP in comparison to pure NIA-based ratios.

be implemented starting in 2012; this will raise the cost of consumption goods in the future relative to the costs of consumption goods before the policy is implemented. As a result, consumers shift their consumption away from future periods and towards the present, increasing consumption in 2010 relative to the reference scenario. In 2020, IGEM, ADAGE and EPPA show a decrease in consumption between 0.5% and 0.7% ($60 to $80 billion), and MRN–NEEM reports a 1.4% ($171 billion) decrease in consumption. The consumption impacts in 2050 across all models fall between 2.3% and 2.8% ($475 and $785 billion) with IGEM on the low end, ADAGE on the high end in percentage terms, and MRN–NEEM on the high end in absolute terms.

The highest consumption impacts are found in the 167 $GtCO_2e$ scenario. In 2020 the consumption losses range from 0.9% ($104 billion) in IGEM to 2.6% ($316 billion) in MRN–NEEM. In 2050 the losses range from 3.5% (876 billion) in EPPA and 3.6% ($748 billion) in IGEM to 4.7% ($1246 billion) in ADAGE.

Another way to view the consumption impacts is to translate the overall U.S. consumption loss into per household consumption loss. Fig. 12 shows annual consumption losses on a per household basis, assuming an average household size of 2.5 persons. The figure also shows the annual net present value of the per household consumption impact, discounted back to 2010 using a 5% discount rate. In general, the per household consumption impacts tend to increase over time in real terms, and in net present value terms the impacts are closer to constant over time, decreasing over time in some cases and increasing over time in others.

In the 287 $GtCO_2e$ scenario in 2020, per household consumption impacts range from a $55 increase in ADAGE to a $492 consumption loss in MRN–NEEM, with EPPA and IGEM showing consumption losses of $65 and $58, respectively. In 2050, the range is from a $100 increase in per household consumption in EPPA to a $1637 per household consumption loss in MRN–NEEM, with ADAGE and IGEM showing $717 and $444 consumption losses per household, respectively. The net present value of the per household consumption impacts in 2020 ranges from a $34 increase in ADAGE to a $302 decrease in MRN–NEEM. In 2050 the range is from a $14 increase in EPPA, to a $233 decrease in MRN–NEEM. The annual average of the 2020 through 2050 per household net present value consumption impacts ranges from $30 in EPPA to $262 in MRN–NEEM, with ADAGE and IGEM falling closer to EPPA at $54 and $56 respectively.

In 2020, per household consumption losses in the 203 $GtCO_2e$ scenario range from $437 in IGEM to $1272 in MRN–NEEM. In 2050, the low end of the range is a $2736 consumption loss per household from IGEM, and the high end of the range is $4584 consumption loss per household from ADAGE. Averaging over the 2020 through 2050 time frame, the annual net present value of the per household consumption losses are $366 in IGEM and $715 in MRN–NEEM, with ADAGE and EPPA falling in between at $556 and $456 respectively.

Per household consumption losses are the highest in the 167 GtCO2e scenario. In 2020 the losses fall between $758 from IGEM and $2349 from MRN–NEEM, and in 2050 the low end of the losses is $4309, again from IGEM and $7797 from ADAGE. In net present value terms, the annual 2020 though 2050 average of the per household consumption loss is $606 in IGEM, $768 in EPPA, $1196 in MRN–NEEM, and $1210 in ADAGE.

6. Summary

The results from the EMF 22 U.S. transition scenarios exercise presented in this paper allow for a comparison across six models that have been used for various analyses of climate change issues, and across three scenarios that span a wide range of potential U.S. emissions

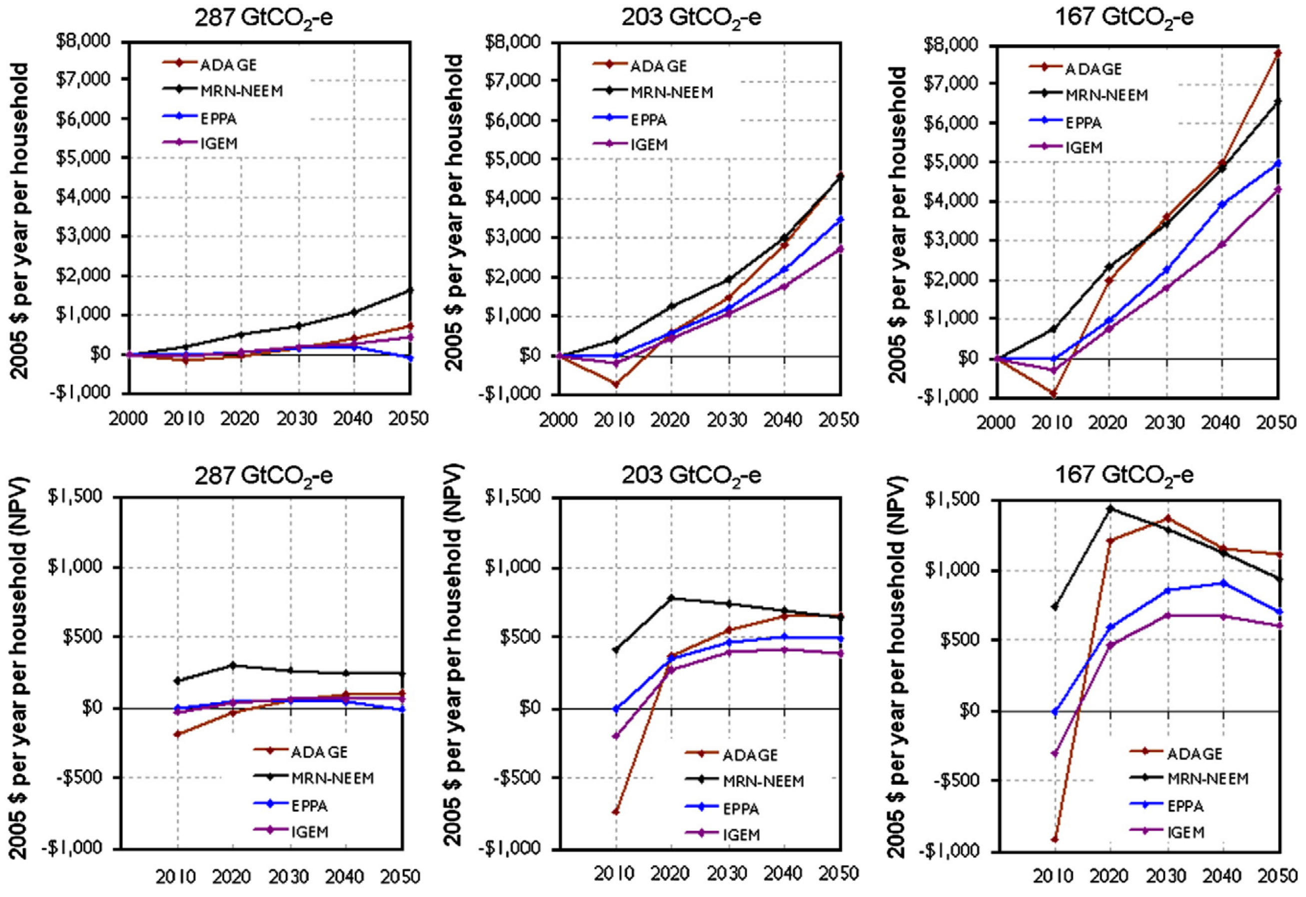

Fig. 12. Household consumption impacts.

targets. Some of the key insights from this paper are described in this summary.

What are the costs of different levels of emissions reductions? The costs of different levels of action can be measured in different ways and vary across models. The allowance prices in 2020 range from \$0/tCO$_2$e to \$20/tCO$_2$e in the 287 GtCO$_2$e scenario, and from \$54/tCO$_2$e to \$113/tCO$_2$e in the 167 GtCO$_2$e scenario. Another way to measure costs is the household consumption loss. The annual average of the 2020 through 2050 per household consumption impacts in net present value terms translate the average impact of the emissions limits in future years on household consumption into an equivalent loss of household consumption today. Costs measured in this way range between \$30 and \$262 in the 287 GtCO$_2$e scenario, between \$366 and \$715 in the 203 GtCO$_2$e scenario, and between \$606 and \$1210 in the 167 GtCO$_2$e scenario.

How will the reductions be allocated across time? Emissions reductions tend to increase over time as allowance prices rise, old existing capital stock retires, and technology advances. Because allowance paths are generally "front-loaded" even with this pattern of increasing abatement over time, the models in this study tend to show that allowances are banked in the early years and that this bank is drawn down in the later years of the policy.

How will reductions be allocated across sectors? By design, a cap-and-trade system does not require equal emissions reductions from all sectors. Instead, the marginal cost of abatement is equalized across sectors, and sectors that have the most low-cost abatement opportunities provide the greatest amount of abatement. All of the models participating in this study show that in each of the scenarios analyzed, emissions reductions in the electricity sector are greater than those in the transportation sector.

What are the implications of climate policy for the energy producers and consumers? The imposition of climate policy substantially changes the energy system. Just how the energy system changes varies across models and depends on the stringency of the scenario. However, all models show a substantial move towards low-carbon technologies, particularly within the electricity sector. By 2050, between 39% and 62% of total primary energy comes from low-carbon sources in the 203 GtCO$_2$e scenario compared to between 12% and 28% in the reference scenario. Low-carbon technologies play a greater role in the electricity sector, and their share of generation in the 203 GtCO$_2$e scenario is between 79% and 97% in 2050, compared to between 24% and 40% in the reference scenario.

This paper has only scratched the surface of the insights that can be gained from this exercise. All of the model outputs presented here are available from the EMF website (http://emf.stanford.edu/research/emf22/) and can be used to explore a wide range of issues beyond those addressed in this study.

7. Other issues addressed in this study

The results of the EMF 22 U.S. transition scenarios exercise presented in this overview paper cover just the broad insights from the core scenarios of the exercise. In their individual papers, all of the modeling teams provide additional insights into the economic analysis and policy assessment of climate mitigation goals by conducting additional analyses beyond the required core U.S. transition scenarios. The range of additional issues analyzed include: the effects of technology availability on costs and GHG reductions; the importance of the assumptions about economic growth and technology costs; the implications of the availability of offsets; impacts on trade and emissions leakage; and the impact of complementary policies, among others. This section highlights a few of these additional issues addressed in the individual papers.

All of the models in the study evaluate the effects of technology availability on costs and GHG reductions and find that the compliance cost of any of the GHG mitigation goals depends critically on the cost and availability of low-emitting technologies. The MiniCAM paper (Kyle et al., 2009-this volume) explores six different technology variants and finds allowance prices that roughly bracket those of the other five participating models. The authors also assess the implications of technology availability and the time path of emissions reductions. Other papers look at the inclusion of economic incentives, e.g., subsidies or bonus allowances, as a means of accelerating the adoption of advanced technologies. The EPPA paper (Paltsev et al., 2009-this volume) explores differences in the deployment and penetration of advanced technologies when assumptions about technology cost change.

Given the importance on cost containment of the use of offsets, most of the papers also run sensitivity analyses on the availability and use of offsets. Offsets are defined as GHG reductions that take place outside of the mandate-covered sectors (e.g. enhanced forest sequestration), and that can be purchased by a covered entity to fulfill its compliance obligation. Offsets do face additional regulatory challenges to ensure that they are permanent, independently verifiable, enforceable, measurable, and transparent. The papers explore the extent to which offsets can reduce costs by allowing additional sources of abatement to contribute to achieving the emissions reduction goals.

The EPPA (Paltsev et al., 2009-this volume) and MERGE (Blanford et al., 2009-this volume) papers cover the importance of the assumptions about economic growth and technology costs. Both papers contrast the resulting GHG emissions projections from different assumptions as to the long-term economic growth rate for the U.S. economy, and show how important these reference scenario growth assumptions are in determining the cost of meeting various emissions targets.

Many of the climate proposals under consideration by policy makers include policies that are intended to be complementary to the cap-and-trade system. These policies are generally designed to achieve additional abatement outside of the cap-and-trade system, or to encourage a particular type of abatement within the cap-and-trade system. Examples of such policies include renewable portfolio standards, transportation fuel standards, and efficiency regulations, among many others. These types of policies have the potential to reduce costs if they correct a pre-existing market failure, or to increase costs if they shift investment away from the least-cost options and toward meeting these specific mandates. The impact of some of these types of policies on costs is explored in the EPPA (Paltsev et al., 2009-this volume) and MRN–NEEM (Tuladhar et al., 2009-this volume) papers.

Another area of recent high interest from policymakers is the impacts of U.S. GHG reduction goals on emission leakage and competitiveness of energy-intensive and trade-exposed industries, and the effectiveness of measures such as border tax adjustments that are designed to mitigate these impacts. The ADAGE paper (Ross et al., 2009-this volume) explores the impact of an international reserve allowance requirement, or border tax adjustment, on the U.S. energy-intensive manufacturing sector, in terms of output, trade, and emissions leakage.

Finally, the issue of cost incidence on different sectors from a U.S. GHG mitigation policy is treated in the IGEM paper by Goettle and Fawcett (2009-this volume). They examine the output and price impacts of U.S. GHG reduction goals on 35 production sectors, and find that while the economy-wide impacts of GHG reduction goals are estimated to be small even in the most stringent policy, there are much larger impacts in certain energy sectors, while other sectors of the economy experience much smaller losses, or even some gains in certain cases. The paper goes on to explore how the capital and labor incomes are affected in various sectors, and ultimately how household decisions and welfare are influenced by different policies.

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