MIT Joint Program on the Science and Policy of Global Change

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Jennifer Morris, Sergey Paltsev, John Reilly[†]

Abstract

Marginal abatement cost (MAC) curves, relationships between tons of emissions abated and the CO_2 (or GHG) price, have been widely used as pedagogic devices to illustrate simple economic concepts such as the benefits of emissions trading. They have also been used to produce reduced form models to examine situations where solving the more complex model underlying the MAC is difficult. Some important issues arise in such applications: (1) are MAC relationships independent of what happens in other regions? (2) are MACs stable through time regardless of what policies have been implemented in the past?, and (3) can one approximate welfare costs from them? This paper explores the basic characteristics of MAC and marginal welfare cost (MWC) curves, deriving them using the MIT Emissions Prediction and Policy Analysis (EPPA) model. We find that, depending on the method used to construct them, MACs are affected by policies abroad. They are also dependent on policies in place in the past and depend on whether they are CO_2-only or include all GHGs. Further, we find that MACs are, in general, not closely related to MWCs and therefore should not be used to derive estimates of welfare change. It would be a great convenience if a reduced-form response of a more complex model could be used to reliably conduct empirical analysis of climate change policy, but it appears that, at least as commonly constructed, MACs may be unreliable in replicating results of the parent model when used to simulate GHG policies. This is especially true if the policy simulations differ from the conditions under which the MACs were simulated. Care is needed to derive MACs under conditions closely related to the policy under consideration. In such a circumstance they may provide approximate estimates of CO_2 or GHG prices for a given policy constraint. They remain a convenient way to visualize responses to a range of abatement levels.

Contents

1. INTRODUCTION

Marginal abatement cost curves (MACs), relationships between tons of emissions abated and the carbon dioxide (CO_2) or greenhouse gas (GHG) price, have been the subject of many studies. In 1998 Ellerman and Decaux produced a much-used set of MACs from an early version of the MIT Emissions Prediction and Policy Analysis (EPPA) model. The EPPA model has since

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evolved a great deal (Paltsev *et al.*, 2005), leading us to consider the re-estimation of a set of new MACs that better represent abatement costs as we now understand them given the advances and improvements we have made in modeling global greenhouse gas emissions. During this process a number of issues have arisen: the stability of MACs to policies abroad, stability over time and dependency of MACs on previous policies, using MACs as a measure of welfare, and the inclusion of all GHGs. This paper explores these issues and offers sets of updated MACs from the EPPA model that analysts may find useful under some conditions as well as some cautions on their use.

Marginal abatement cost refers to the cost of eliminating an additional unit of emissions. Total abatement cost is simply the sum of the marginal costs, or the area under the MAC curve. A MAC curve for CO_2 emissions abatement can be constructed by plotting CO_2 prices (or equivalent CO_2 taxes) against a corresponding reduction amount for a specific time and region (Ellerman and Decaux 1998). Construction of MACs involves multiple runs of a model to get different price-quantity pairs. MAC curves can be constructed for a single GHG or a combination GHGs if one has a weighting system for trading among them such as the Global Warming Potential (GWP) index. MACs have been widely used as pedagogic devices to illustrate simple economic concepts such as the benefits of emissions trading. They have also been used to produce reduced-form models to examine situations where solving the more complex model underlying the MAC is difficult.

Ellerman and Decaux (1998) and Klepper and Peterson (2006) are two of the most commonly-cited MAC studies. Ellerman and Decaux investigated the robustness of MACs with respect to different levels of abatement among regions and different scopes of emission trading. According to their definition, robustness refers to whether the MAC is virtually the same whatever the reductions of other countries. Klepper and Peterson (2006) also explored the robustness issue, arriving at somewhat different conclusions than Ellerman and Decaux (1998).

Issues not explored by these previous authors include the stability of the MACs over time and closely-related path dependency, whether measures of welfare can be derived from MACs, and the implications of expanding MACs to include all GHGs. MACs may change over time as a result of technological opportunities and resources and other conditions that may differ over time. By path dependency we mean specifically: does a MAC constructed for a country in period t=n depend on GHG policies implemented in periods t= 0 through t=n-1? Many analyses, such as those that seek to demonstrate the potential benefits of emissions trading, must interpret MACs as equivalent to Marginal Welfare Cost (MWCs) Curves. Since the EPPA model includes an explicit evaluation of welfare change, we are able to construct direct measures of MWC from the EPPA runs and compare them to MACs. Finally, since the early work of Ellerman and Decaux (1998) and Klepper and Peterson (2006), the importance of considering non-CO_2 GHGs in the design of policy has been realized and so we consider how that inclusion changes the basic shape of estimated MACs.

In section 2 we describe the version of the EPPA model used here and how it differs in broad terms from the earlier EPPA version used by Ellerman and Decaux (1998). We then compare the MACs from this model with those obtained by Ellerman and Decaux in Section 3. In Section 4 we also test the stability of MACs to policies abroad using the new version of EPPA following protocols developed by Klepper and Peterson (2006). In Section 5 we explore issues that were not investigated by Ellerman and Decaux or Klepper and Peterson, including stability over time and path dependency, the relationship of MACs to MWCs, and the inclusion of all GHGs in a policy. Section 6 then takes into account all the issues previously discussed to develop a set of MACs that, if one must rely on them, are derived under conditions that are relevant to current policy discussions. Section 7 offers conclusions and cautions on the use of MACs.

2. THE EPPA MODEL

To construct the MAC curve we use the latest version of the MIT Emissions Prediction and Policy Analysis (EPPA) model. The standard version of the EPPA model is a multi-region, multi-sector recursive-dynamic representation of the global economy (Paltsev *et al.*, 2005). In a recursive-dynamic solution economic actors are modeled as having "myopic" expectations.[1] This assumption means that current period investment, savings, and consumption decisions are made on the basis of current period prices. This version of the model is applied below.

The level of aggregation of the model is presented in **Table 1**. The model includes representation of abatement of non-CO_2 greenhouse gas emissions (CH_4, N_2O, HFCs, PFCs and SF_6) and the calculations consider both the emissions mitigation that occurs as a byproduct of actions directed at CO_2 and reductions resulting from gas-specific control measures. Targeted control measures include reductions in the emissions of: CO_2 from the combustion of fossil fuels; the industrial gases that replace CFCs controlled by the Montreal Protocol and produced at aluminum smelters; CH_4 from fossil energy production and use, agriculture, and waste, and N_2O from fossil fuel combustion, chemical production and improved fertilizer use. More detail on how abatement costs are represented for these substances is provided in Hyman *et al.* (2003).

Non-energy activities are aggregated to six sectors, as shown in the table. The energy sector, which emits several of the non-CO_2 gases as well as CO_2, is modeled in more detail. The synthetic coal gas industry produces a perfect substitute for natural gas. The oil shale industry produces a perfect substitute for refined oil. All electricity generation technologies produce perfectly substitutable electricity except for Solar and Wind which is modeled as producing an imperfect substitute, reflecting its intermittent output. Biomass use is included both in transport fuel and electric generation although it does not penetrate the electric sector in these simulations.

The regional and sectoral disaggregation also is shown in Table 1. There are 16 geographical regions represented explicitly in the model including major countries (the US, Japan, Canada, China, India, and Indonesia) and 10 regions that are an aggregations of countries. Each country/region includes detail on economic sectors (agriculture, services, industrial and

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[1] The EPPA model can also be solved as a forward looking model (Gurgel *et al.*, 2007). Solved in that manner the behavior is very similar in terms of abatement and CO_2-e prices compared to a recursive solution with the same model features. However, the solution requires elimination of some of the technological alternatives.

household transportation, energy intensive industry) and a more elaborated representation of energy sector technologies.

Table 1. EPPA Model Details.

Country or Region[†]	**Sectors**	**Factors**
Developed	***Non-Energy***	Capital
United States (USA)	Agriculture (AGRI)	Labor
Canada (CAN)	Services (SERV)	Crude Oil Resources
Japan (JPN)	Energy-Intensive Products (EINT)	Natural Gas Resources
European Union+ (EUR)	Other Industries Products (OTHR)	Coal Resources
Australia & New Zealand (ANZ)	Transportation (TRAN)	Shale Oil Resources
Former Soviet Union (FSU)	Household Transportation (HTRN)	Nuclear Resources
Eastern Europe (EET)	***Energy***	Hydro Resources
Developing	Coal (COAL)	Wind/Solar Resources
India (IND)	Crude Oil (OIL)	Land
China (CHN)	Refined Oil (ROIL)	
Indonesia (IDZ)	Natural Gas (GAS)	
Higher Income East Asia (ASI)	Electric: Fossil (ELEC)	
Mexico (MEX)	Electric: Hydro (HYDR)	
Central & South America (LAM)	Electric: Nuclear (NUCL)	
Middle East (MES)	Electric: Solar and Wind (SOLW)	
Africa (AFR)	Electric: Biomass (BIOM)	
Rest of World (ROW)	Electric: Gas Combined Cycle	
	Electric: Gas with CCS	
	Electric: Coal with CCS	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	
	Liquids from Biomass (BI-OIL)	

[†] Specific detail on regional groupings is provided in Paltsev *et al.* (2005).

When emissions constraints on certain countries, gases, or sectors are imposed in a CGE model such as EPPA, the model calculates a shadow value of the constraint which is interpretable as a price that would be obtained under an allowance market that developed under a cap and trade system. Those prices are the marginal costs used in the construction of MAC curves. They are plotted against a corresponding amount of abatement, which is the difference in emissions levels between an unconstrained business-as-usual reference case and a policy-constrained case.

The solution algorithm of the EPPA model finds least-cost reductions for each gas in each sector and if emissions trading is allowed it equilibrates the prices among sectors and gases (using GWP weights). This set of conditions, often referred to as “what” and “where” flexibility, will tend to lead to least-cost abatement. Without these conditions abatement costs will vary among sources and that will affect the estimated welfare cost—abatement will be least-cost within a sector or region or for a specific gas, but will not be equilibrated among them. The mixed complementarity solution approach means that least-cost is defined in terms of the prices (for fuels, electricity, capital, labor, and other goods) faced by producers and consumers. It does not necessarily lead to a welfare optimum if there are distortions (*e.g.* taxes) and to the extent the behavior of individual agents have macroeconomic consequences such as affecting the terms of trade of a country/region.

The results depend on a number of aspects of model structure and particular input assumptions that greatly simplify the representation of economic structure and decision-making. For example, the difficulty of achieving any emissions path is influenced by assumptions about population and productivity growth that underlie the no-policy reference case. The simulations also embody a particular representation of the structure of the economy, including the relative ease of substitution among the inputs to production and the behavior of consumers in the face of changing prices of fuels, electricity and other goods and services. Further critical assumptions must be made about the cost and performance of new technologies and what might limit their market penetration. Alternatives to conventional technologies in the electric sector and in transportation are particularly significant. Finally, the EPPA model draws heavily on neoclassical economic theory. While this underpinning is a strength in some regards, the model fails to capture economic rigidities that could lead to unemployment or misallocation of resources nor does it capture regulatory and policy details that can be important in regulated sectors such as power generation.

The Ellerman-Decaux analysis was based on version 1 of the EPPA model and we are now using a version 4 of the model. The changes in the data and structure of the model are extensive. Version 1 of the model relied on early version of the OECD GREEN model database and retained much of the structure of that model. The basic Input-Output (I-O) structure and data were fairly outdated. Versions 2 through 4 are based on Global Trade Analysis Project (GTAP) data with successive versions identifying revised and updated GTAP releases. EPPA version 4 is based on GTAP release 5 with a benchmark year of 1997.

Another important difference is the disaggregation of technological options and addition of alternative energy technologies. EPPA version 1 was a fairly standard CGE model derived from I-O and National Input and Product Account (NIPA) data. Significant limitations of these data are lack of detail in the energy sector and the absence of any description of technology/sectors that were not actually in commercial use in the base year. For example, power generation is generally a single sector in these data that purchases fuels and other inputs, with returns (wages and rents) to factor inputs—labor and capital. In using these data to parameterize a production function, substitution between fuels and capital and labor represent a mix of possible improvements in the efficiency of conversion of fuels to electricity and a switch to other generation options—hydro, nuclear, renewables—that produce electricity without fossil fuels. Simple substitution elasticities between fuels and capital and labor thus poorly capture the different costs and potential resource limitations of these different technological options over the longer run or over relatively extreme changes in relative prices, such as when a tight CO_2 constraint is implemented. In particular, the Constant Elasticity of Substitution (CES) production function used in the model has the property that substitution becomes more difficult as one moves farther from the benchmark data. This property is sometimes referred to as the share-preserving property of the formulation. If there is a discrete alternative to fossil generation that is essentially a perfect substitute at some cost—nuclear power or coal generation with carbon capture and storage—a CES representation of the aggregate sector will poorly capture the possibility of switching completely to this alternative. Trying to capture this process in a simple CES production function can yield too much substitution at lower CO_2 prices but too little at higher prices. Also, the provision of own-supplied household transportation—personal automobiles—is generally not broken out in the basic input-output structure.

Similarly, advanced technologies such as renewables (solar and wind), biomass electric, liquid biofuels, shale oil, coal gasification, and CCS are not represented in base data in EPPA 1 because they were not operating at all or at least not at significant commercial levels when the data were assembled. Emissions and abatement opportunities for non-CO_2 GHGs were also not represented in these data. Thus, version 1 of the model was largely limited to crude oil, refined oil, natural gas, coal, and a single electric generation sector, and a similarly reduced set of resource inputs. The regional aggregations have also evolved. EPPA version 1 had 12 regions and version 4 has 16, allowing a separate representation of Canada, Australia/New Zealand, Mexico, and Indonesia. Regional aggregations were also reformulated to contain contiguous areas whereas the previous formulation attempted to aggregate economies with like attributes such as those that were energy exporters. In that regard, regional aggregation is always less than a satisfactory solution at some level and as interests vary different regional aggregations may be preferred—and it is hard to predict how different aggregations might affect key results. Similarly, the current version represents demand sectors in more detail, breaking out both household and commercial transportation and the service sector. Overall, version 4 is more highly disaggregated in terms of sector and regional coverage and includes explicit representation of advanced technologies. It is now more of a hybrid model—combining elements of a top-down model based on macroeconomic data with bottom-up information on engineering cost data—whereas early versions of the model were more highly aggregated and drew almost exclusively from basic I-O and NIPA data.

3. COMPARISON OF NEW EPPA MAC CURVES WITH OLD CURVES

Ellerman-Decaux obtained MACs for 2010 for policy constraints in which OECD regions pursued proportional reductions of 1, 5, 10, 15, 20, 30, and 40% below reference emissions in 2010 and other regions did nothing. In that version of the model, OECD included USA, JPN, EEC (EC-12, the European Union as of 1992), and OOE (all other OECD countries, including Canada, Australia, New Zealand, Scandinavia and Turkey). We replicated this policy with the new EPPA version, in which OECD includes the same countries although they are aggregated a bit differently (USA, JPN, EUR (EU-27 plus Iceland, Norway, and Liechtenstein), CAN, and ANZ). **Figure 1** below compares the MACs for USA, EUR, and JPN obtained from the two versions of the model. Both curves are in units of mmt of C as in the original Ellerman and Decaux work rather than as tons of CO_2 that has become more standard. However, we have updated the Ellerman and Decaux curves to 2005 dollars using the US GDP implicit price deflator index.

The new MACs have lower costs at high levels of abatement, and at all levels of abatement for JPN and EUR. For the USA the cost differences are smaller and the new MAC is actually somewhat above the old until about 500 mmtC. The difference between the curves is greatest for Europe. Some of this difference is likely due to aggregation of the eastern European countries. However, also note that the previous versions of the MACs are clearly convex to the origin, with marginal costs increasing at an increasing rate, not a surprising result given the CES structure. Conversely, the new MACs concave to the origin, at least through the abatement levels simulated here. This behavior is due to the addition of advanced technologies that enter as perfect or near-perfect substitutes for fossil intensive technologies. Examination of the detailed results indicates that biofuels are coming in at the higher prices, a technology which was not represented in the earlier version of the model.[2]

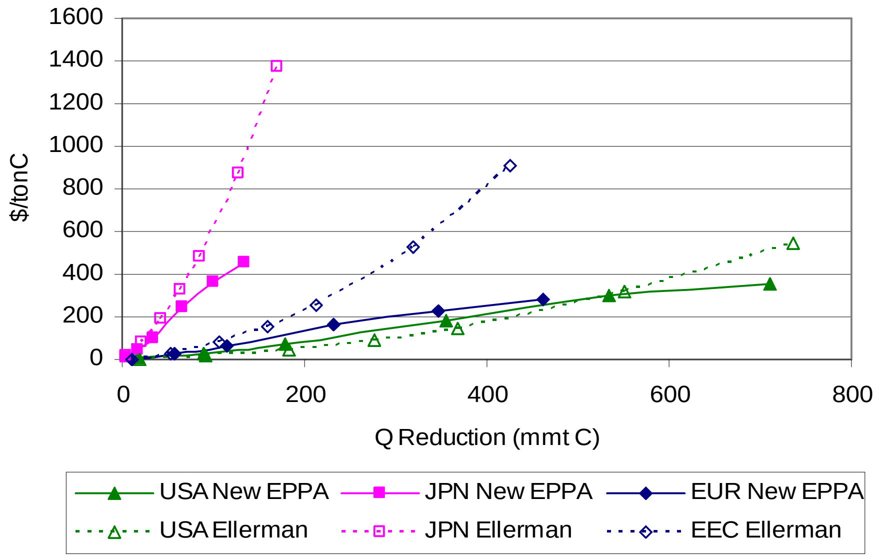

Figure 1. New MACs vs. Old MACs in 2010.

Ellerman and Decaux were focused on the shorter term, concentrating on 2010 in particular as that year represented the Kyoto period. With policy discussions looking beyond Kyoto, at least to 2050, the resolution of abatement opportunities further in the future becomes more important. We thus construct a set of cases that assume all countries and regions pursue the same policy, which reduces CO_2 emissions by 1, 5, 10, 20, 30, 40, and 50%, below the reference no policy level. The policy starts in 2010 and remains the same through 2050 for each point on the MAC. That is, the MACs are constructed by having all countries in all time periods first at 1% below reference, then at 5%, then 10%, *etc.* To focus on the domestic costs of abatement in each region, there is no emissions trading among regions/countries, but implicitly a trading system

[2] Because the CCS technologies are far from ready for commercial penetration at this point they are not available at any price in EPPA until 2025 in these runs and so their addition to the model does not affect the 2010 MAC.

operates *within* each region/country. All marginal costs are expressed as 2005 dollars per ton of CO_2 and the quantities of CO_2 emissions reduced are in million metric tons (mmt) of CO_2. The 2010 MACs are exactly those shown in Figure 1 only in mmt of CO_2 rather than mmt of C, and including an additional point for 50% reductions. **Figure 2** shows the resulting MACs in 2010, 2020, and 2050 for USA, EUR, and JPN.

A striking result in Figure 2 is that the later-year MACs are lower than earlier-year MACs, and this is especially pronounced in the 2050 MAC. In general, later-year MACs have a flatter shape, sometimes even an S-shape or step function. The result is due to (1) the availability of more technological options after 2020 and (2) path dependency which will be demonstrated more directly in Section 5.1. Several of the advanced electric generation options—those that feature CCS—are promising but are at a stage of development where most believe it would take something like a decade to get even a large scale demonstration project completed. Thus, while EPPA has these technologies in the model they are simply prohibited from entry until 2025 at the earliest. Thus, they have no effect on the MACs in 2010 and 2020.

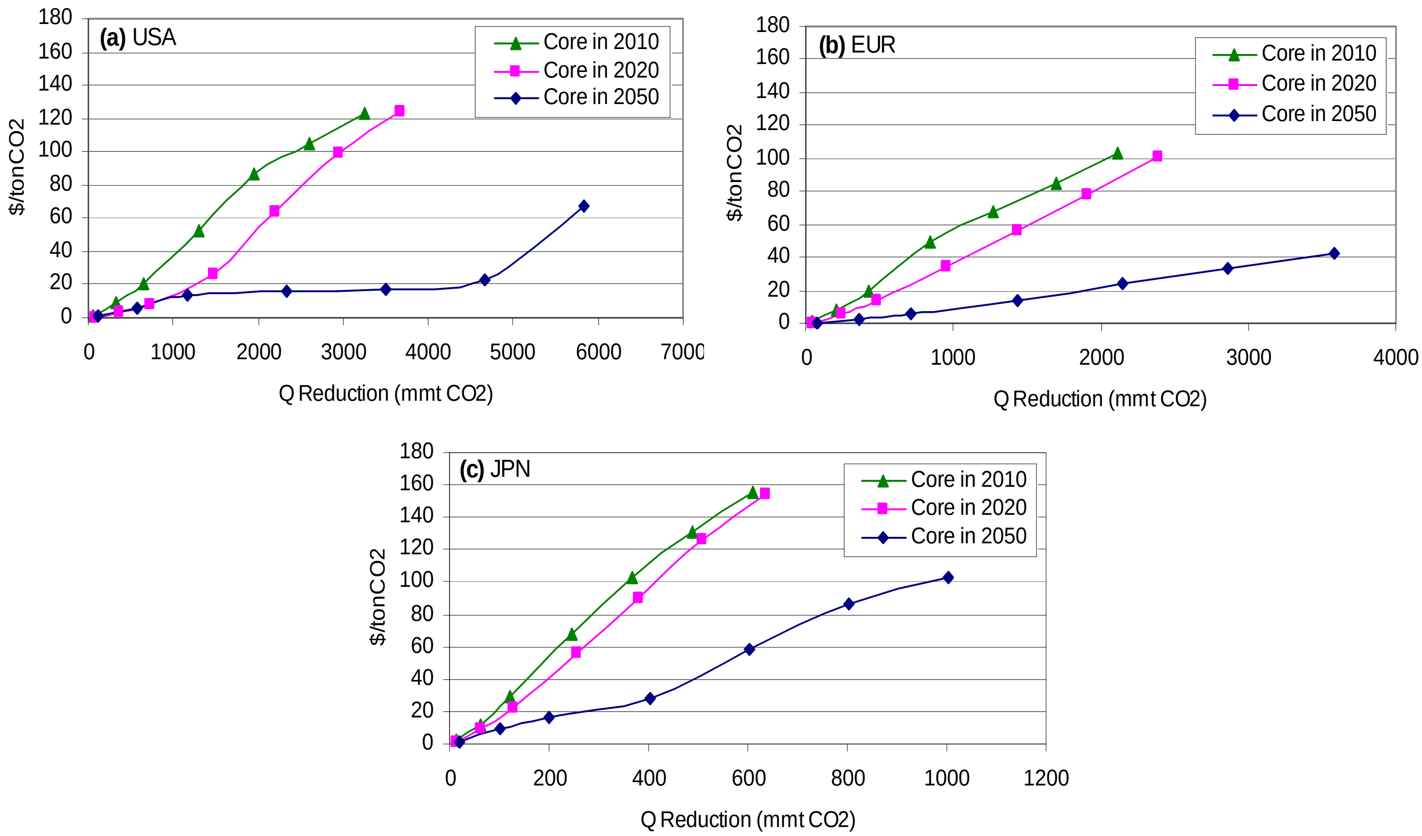

Figure 2. MACs in 2010, 2020, and 2050 when the reduction policy is started in 2010: (a) USA, (b) EUR, and (c) JPN.

As we will see in later sections, path dependency is playing a large role in the shape of the MAC in later years, and so this simulation design where high levels of abatement are simulated from 2010 onward, while useful in demonstrating behavior of the model, is generally not very realistic. Most policies proposals envision a gradual tightening of the reduction over time to avoid unnecessarily high near-term costs. Or, policies envision banking and borrowing—allowing agents to reallocate reductions through time in an economically rational way to again avoid excessive near-term costs.

On a technical note, Ellerman and Decaux (1998) found it convenient to fit a quadratic function to the MAC data. If one wishes to use MACs to estimate CO_2 prices for different levels of abatement then some method of interpolating between simulated price-quantity points is needed. The graphs shown in the Figures above and throughout this paper were produced in Excel with the software's graphing option. The smoothing features embedded in that software produce the smooth curves shown. The existence of more complex MAC shapes, such as for the USA in 2050 as shown Figure 2, leads to questions about the accuracy of interpolations between points. One might be concerned that, for a limited set of points, the position of inflection points may be inaccurately estimated or other inflections may exist. We use the graphs simply to provide a visualization of the differences among MAC points for different countries, time periods, and alternative ways in which the MACs are constructed.

4. STABILITY TO POLICIES ABROAD

One issue explored by Ellerman and Decaux was the stability of MACs to policies abroad. They found that the EPPA-based curves were very stable and therefore robust to other countries' behaviors. A later paper by Klepper and Peterson (2006) challenged this stability using a different CGE model (DART). They attributed the shifts in national MAC curves to the changes in energy prices resulting from different global abatement levels. Ellerman and Decaux's method interpreted trade effects as a shift in the reference level of emissions and MACs were computed from the new baseline with reference emissions adjusted to account for trade effects from policies abroad. Klepper and Peterson found a shifting MAC when they held the baseline unchanged, but obtained a similar result to Ellerman and Decaux when they changed the baseline.The difference in the approaches is a matter of defining the baseline. The Klepper and Peterson approach would say that if the US, for instance, were to adopt a certain reduction in emissions, that reduction would require a higher price (a shift of MAC) if the rest of the world had already acted (and changed energy prices) and produced a different baseline for the US. The Ellerman-Decaux approach would have simply started out from that baseline. There are actually additional ways to design the MAC construction. For example, one approach is to estimate each country's abatement curve when all other countries are doing nothing, and then any terms of trade effects would be due only to actions within the country.

In our view, which approach to use depends on how one sees policy developing and how results from such an exercise might be used. If the country of interest, for example the United States, has remained out of an international agreement while other countries have committed to a clear policy, then what you would like is a MAC estimated with that specific international policy and the baseline for the USA adjusted for that policy, but the USA MAC estimated without changing the international policy level. This first case is that of a country considering unilateral policy action given that they know what policy the rest of the world is pursuing. The country's reference should include the fact that other countries are committed to pursuing policies and take into account whatever impacts those policies have on energy markets. One would not want to have additional trade effects represented in either the position or the slope of the MAC.

Different situations may arise when a country is involved in multilateral negotiations. In such a situation, the baseline a country is working from likely reflects no additional action by others, as all countries would impose a policy simultaneously. However, if the country has proposed additional cuts for itself, and one would like to evaluate the costs of different levels of abatement in that country, then one would like a MAC that was shifted to represent other countries' proposed policies.

The right set of MACs for a country is somewhat less clear when international emissions trading is allowed. Emissions trading will reallocate the reductions among the participating countries. If any effect of the policy on global markets was already embedded in baselines, then MACs estimated without further baseline shift either in position or slope would be appropriate as a first approximation. However, reallocating reductions among countries may affect energy markets. If tight targets in some countries force reductions in petroleum and trading relaxes those impacts and shifts abatement to non-CO_2 GHGs in a country with initially looser targets, that would tend to lower the terms of trade effects in oil markets. Without knowledge of the specific types of differential constraints, any given set of MACs may be well-suited to a particular case but be less appropriate for another.

How much do these different experimental designs affect the MAC? We demonstrate these differences with the EPPA model by creating three cases in which the USA does either a 0, 1, 5, or 10% reduction in each of the years 2010, 2015, and 2020 while (1) the rest of the world does nothing (US ONLY case), (2) Annex 1 countries reduce by 10% in 2010 and 2015 and by 20% in 2020 (ANNX1 case), or (3) the rest of the world reduces by 10% in 2010 and 2015 and by 20% in 2020 (ROW case). The two constructions of the MACs of these policies are shown in **Figure 3** for the US in 2020. When we use the MAC experimental design of Ellerman and Decaux we get the stability they found to policies abroad. When we use the design of Klepper and Peterson we get differences based on other countries' policies. Similar to their result, the percentage differences are quite large at low levels of reductions.

Like Klepper and Peterson we find the difference to be the result of changes in energy prices caused by global abatement that affect countries even though the emission trading systems of countries are not linked. Mitigation policy abroad reduces the world oil price as countries demand less oil in order to meet their reduction targets. At lower oil prices, countries would be inclined to use more oil which would in turn create more emissions. Meeting a reduction target in the face of this situation would therefore require a higher CO_2 price to make alternatives economically attractive. In effect, the CO_2 price needs to be higher to make up for the drop in the world oil price. Another energy price playing an important role is that of biofuels. More stringent mitigation policy abroad also leads to greater global biofuel use, and the resulting higher biofuel prices make reductions more expensive.

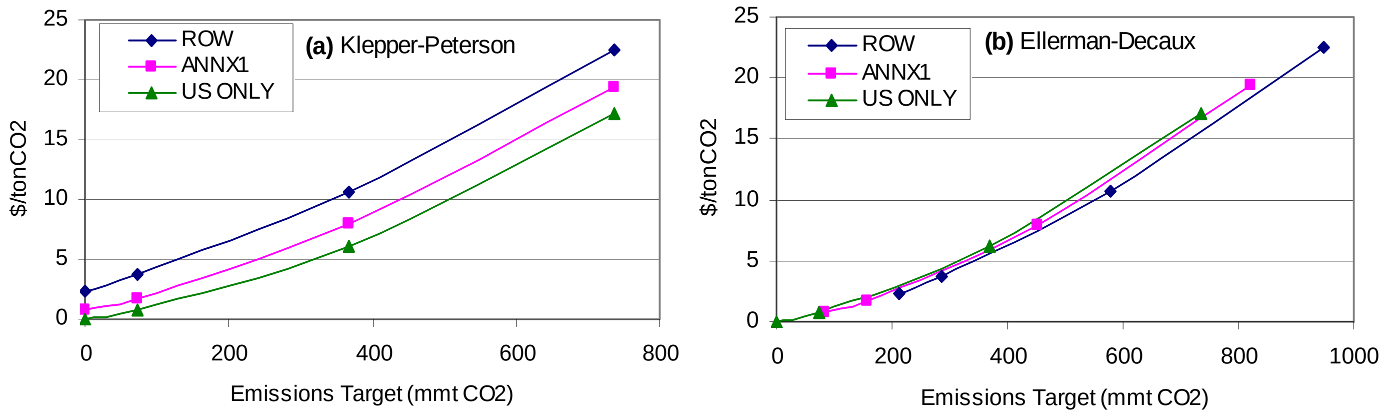

Figure 3. Robustness using different constructions of MACs for 2020: (a) Klepper-Peterson construction and (b) Ellerman-Decaux construction.

Tables 2 and 3 illustrate the point further. The tables show the marginal abatement costs for a given emissions target for the US and China given different global involvement in emissions reductions. It is assumed that the US does nothing until 2020 at which point it must decide which policy to pursue given that either Annex 1 or all other countries have been doing 10% reductions in 2010 and 2015 and 20% reductions in 2020. The same is assumed for China except that China does nothing until 2025 when it must choose a policy.

Table 2. USA 2020 MACs.

USA Emission Target (mmt CO2)	USA MAC ($/tonCO2)		
	US ONLY	*ANNX1*	*ROW*
7569	X	X	0
7442	X	0	X
7357	0	0.79	2.39
7284	0.73	1.75	3.70
6989	6.16	7.90	10.69
6622	17.13	19.37	22.50
5886	45.08	47.94	52.12
5150	64.20	68.83	74.96
4414	80.15	84.15	89.40
3679	103.07	105.27	108.10

We see that the marginal abatement cost changes with the global participation scenario. If, for example, the US had a cap of 6989 mmt that would result in a price of $6.16 if the US pursued the policy alone, but the price would be over 70% higher ($10.69) if the rest of world pursued the policy we described. The results for China are similar in direction but smaller in magnitude because oil imports are not as large in China as they are in the US.

Table 3. CHN 2025 MACs.

CHN Emission Target (mmt CO2)	CHN MAC ($/tonCO2)	
	ANNX1	*ROW*
5013	X	0
4978	0	X
4949	0.22	0.30
4900	0.37	0.55
4702	1.43	1.65
4454	3.10	3.40
3959	8.73	9.38
3464	21.88	23.44
2970	50.81	60.11
2475	82.68	87.48

A few general observations: (1) The different experimental designs for constructing MACs can lead to fairly large differences. (2) There is no universally correct approach as it depends on how the MACs are being used to inform decisions and what other ancillary information is being used—whether shifts in the baseline are being considered separately or not. (3) There are an unlimited number of variants with more or less participation of other countries at different levels of abatement, responding or not to changes in the abatement level of other countries. (4) In principle one would want to produce a set of MACs for the exact conditions one wished to examine, but that entails running the parent model many more times to produce the MAC than would be necessary to simply examine the policy with the parent model. These considerations thus lead to the conclusion that any particular set of MACs can at best only provide a rough approximation of the marginal abatement cost in a particular country, and using them as a basis for a reduced form model has limits in that they will not be completely consistent with different policies simulated with the parent model.

5. ADDITIONAL ISSUES

In this section we consider other important issues that were not investigated by Ellerman and Decaux or Klepper and Peterson. We look at potential path dependency, the relationship between MACs and welfare, and the inclusion of all GHGS in a reduction policy. We construct MACs for USA, JPN, EUR, CHN, IND, and MES to illustrate the affects of each issue.

5.1 Path Dependency

Path dependency refers to whether a MAC constructed for a country in period t=n depends on policies in periods t=0 through t=n-1. In order to explore this issue, we constructed MACs for 2050 for three cases that have different time frames of policy implementation. The first case is that used earlier where all countries are doing the same policy (1, 5, 10, 20, 30, 40, or 50%

reductions) each period starting in 2010. The second case has all countries doing the same policy starting in 2050 and doing nothing before then. The third case develops a more realist path of emissions reductions from 2010 to 2050 that gradually increases and incorporates a delay for developing countries. This path is detailed in **Table 4.** The country for which the MAC is constructed is assumed to pursue either the Annex 1 or Annex 2 path until 2050 when it does either 1, 5, 10, 20, 30, 40, or 50% reductions. **Figure 4** shows the MACs for the three different cases for the USA, EUR, JPN, CHN, IND, and MES in 2050.

Table 4. Path Policy.

Year	2010	2015	2020	2025	2030	2035	2040	2045	2050
ANNX1	10%	10%	20%	20%	20%	35%	35%	35%	50%
ANNX2	0%	0%	0%	10%	10%	20%	20%	20%	35%

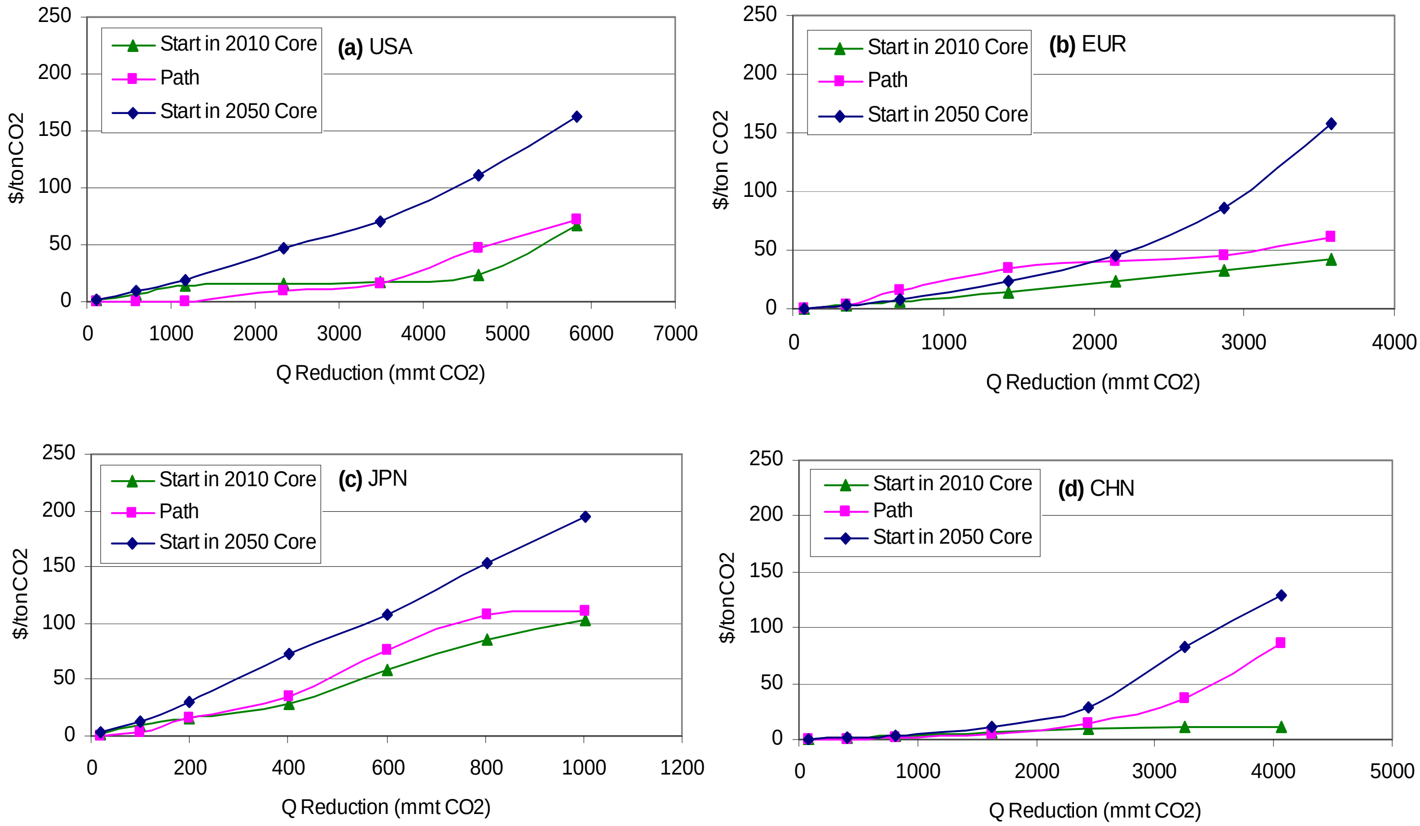

Figure 4. MACs in 2050 when the reduction policy starts in 2010, 2050, or follows a reduction path: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

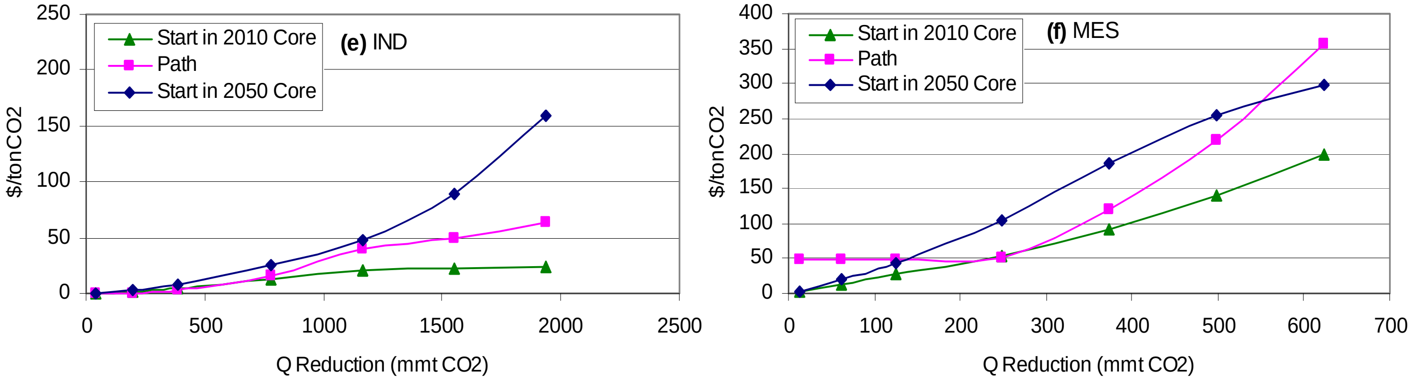

Figure 4 (cont.). MACs in 2050 when the reduction policy starts in 2010, 2050, or follows a reduction path: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

The differences in marginal abatement costs between the three cases are substantial. The figures clearly show that MAC curves for the same time period and region with the same constraint have different shapes depending on what policies were enacted in the past. The stronger and longer the policy in the past, the lower the marginal abatement costs for a given reduction in a given year. This path dependency is a major explanation for the flat and S-shaped 2050 MACs we saw in Section 3 and repeated here.

Interestingly, the 2050 MAC derived from the Path policy in MES does not begin at zero. Investigating further to find the source of the higher starting cost we found that leakage from the rest of world was responsible. In particular, when we simulate the MES with no policy while the rest of the world follows the Path policy emissions in MES are more than double those in the reference. Energy activities are relocated from other countries into MES, where energy sources are located. This increased activity results in significantly higher emissions, meaning even returning to the original reference involves significant cost. This is a fairly extreme example of the Klepper and Peterson result.

Two particular features in the model contribute to path dependency. One is vintaging and the other is the use of a fixed factor that slows penetration of advanced technologies. With regard to vintaging, if there is no policy in place in prior years old capital will emit relatively high amounts of GHGs and replacement of it is only possible when it depreciates away. Until that depreciation occurs reductions need to be found in other sectors of the economy where the marginal costs are higher.

The fixed factor for advanced technologies represents an initially limited amount of technical know-how and engineering capacity to install the new technology. That capacity only expands if and as investment in the technology occurs. This strongly constrains the capacity of the advanced technology in the first couple of periods in which it is available and demanded. With a tight policy in early years (*e.g.* 50% reduction), there is strong demand for advanced technologies like CCS and so by 2050 the fixed factor is no longer a significant limitation on investment. However, if there is no previous policy then the fixed factor will limit CCS investment. When we create the MACs with equal reductions in all periods we saw from the series of them as plotted in Section 3 that the CO_2 prices for a given percentage reduction are actually falling over time. Hence, in earlier periods there is, if anything, over-investment in clean technology and over-expansion of the fixed factor. The existence of vintaged capital, which was efficient at the higher earlier prices, means that there is abatement in later years that is not economic given the falling CO_2 prices if the full investment cost were to be taken into account. Thus, particularly for large reductions this method of constructing the MACs is fairly unrealistic.

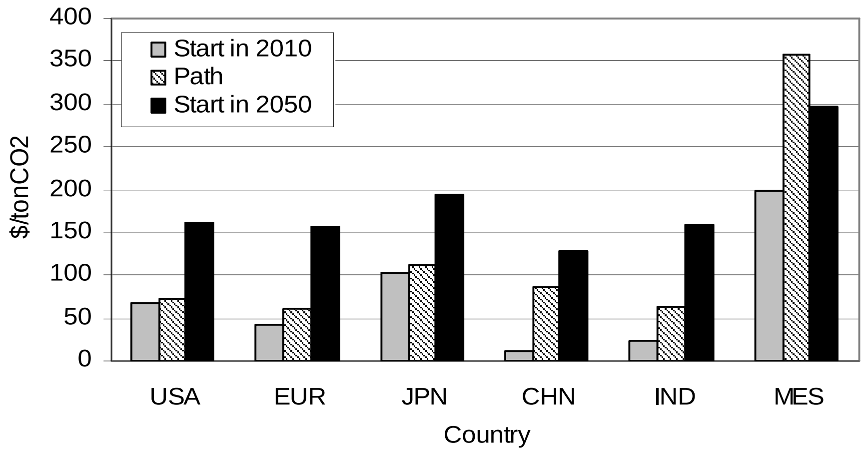

Figure 5. Marginal abatement costs in 2050 of a 50% reduction policy that starts in 2010, 2050, or follows a reduction path.

Figure 5 focuses on the 2050 CO_2 price for a 50% reduction to illustrate the large differences depending on the time frame of the policy. The case in which all countries pursue 50% reductions in all years starting in 2010 is the least costly in 2050 because it has had a stringent 50% reduction policy in all periods leading up to 2050, so by 2050 there has been substantial investment in cleaner technology and in the fixed factor that makes it possible to achieve a policy at low marginal abatement costs in 2050. The Path policy is more expensive than this case because, although the policy has been in place for developed countries since 2010 and developing countries since 2025, the policies have not been as stringent as a 50% reduction policy each period. Therefore less investment has been made, and more is needed for a policy in 2050. A policy just started in 2050, is of course the most expensive as the capital stock in place is dirty because there has been no incentive in earlier years for cleaner investment and there has been no build-up in the capacity to install cleaner advanced technologies.[3] In MES the Path policy is more costly than the policy started in 2050 due to the leakage issue explained above. Examining emissions over the full time horizon to 2050 when MES does nothing while the world pursues the Path policy shows that leakage to the MES builds up gradually over time as more

[3] Solving the model as a forward-looking problem would reduce the high costs in 2050 because agents would know the policy was coming and would start adopting cleaner technology in anticipation of the policy. One should see effects in previous periods that spread some of the costs earlier and reduce the total cost. Unfortunately, solving the forward-looking problem generally requires simplification of the model and explicit multiple vintages of capital are one of the features that generally need to be eliminated to make the forward-looking solution feasible. Solving the forward-looking problem would not help MAC construction as the MACs would not only be path dependent but would depend also on future policy conditions, or expectations of them.

energy intensive industry locates there. In contrast, a policy started in 2050 everywhere means that there has less time for significant leakage to build up and so emissions and the cost of reductions are lower.

5.2 Measure of Welfare

Neither Ellerman and Decaux nor Klepper and Peterson investigated the relationship of MACs to welfare, even though many users of MACs integrate them to measure “gains from trade” which is a welfare concept. In an idealized neoclassical economic setting, first-order conditions from consumer welfare maximization involve consumers equating marginal welfare to the price of all goods, and similarly producers setting marginal cost to the price of all goods. On that basis, the MAC and marginal welfare cost (MWC) curves should be identical. However, actual economies represented in computable general equilibrium models can diverge from this partial equilibrium, first-best neoclassical world. Goulder (1995) showed generally that the CO_2 price can be a poor indicator of welfare when there are other distorting policies. Metcalf *et al.* (2004) demonstrate how CO_2 pricing can interact with pre-existing energy taxes to exacerbate dead-weight loss and raise the welfare cost of mitigation policy. Paltsev *et al.* (2007) illustrate the effects of tax interactions and terms of trade effects diagrammatically and show how it can result in emissions trading being welfare worsening. Webster *et al*., (2008) estimates welfare benefits for emissions trading in a stochastic setting using a reduced form MAC model and the parent model and show large differences. Thus, the fact that tax distortions and terms of trade effects, the source of instability in Klepper and Peterson’s (2006) MACs, can also affect welfare estimates is not a new result. In this regard, it is useful to consider the welfare results from a CGE model to be driven by two components: (1) the direct welfare costs of abatement that can be measured as the integral under the MAC and (2) indirect welfare effects that involve terms of trade effects, interactions with other distortions, and saving and growth effects from policies in earlier years. Paltsev *et al.* (2007) derive from a CGE model a method to estimate the direct costs and show them to be nearly identical to the MAC integration but leaving a substantial residual difference attributable to other factors.

Here we show divergence in welfare and marginal abatement costs by estimating MWC curves that can then be compared to MAC curves. To derive MWC curves we note that marginal welfare cost refers to the welfare loss associated with abating an additional unit of emissions. For our welfare measure we use equivalent variation and we monetize it as a change in aggregate market consumption for a representative agent in a region. The CO_2 price simulated by the model is a marginal concept, directly related to the shadow value of a Lagrangian maximization problem. However, the welfare index monetized as equivalent variation is a total cost concept—simply dividing the monetized welfare loss for a particular policy level compared to no policy gives an average loss rather than a marginal loss. We therefore numerically approximate marginal welfare change by calculating the welfare change over a discrete but small change in the abatement level, and then use the average welfare change over that small discrete change as an approximation of the marginal welfare change.

To calculate the marginal welfare cost we ran the seven reduction policies (1, 5, 10, 20, 30, 40, and 50% reductions) plus another seven policies requiring an additional 1% reduction (*i.e.* 2, 6, 11, 21, 31, 41, and 51% reductions). We then calculated the change in welfare resulting from the additional 1% of reductions (for example the change in welfare when comparing a 40% reduction to a 41% reduction). To make this cost measure comparable to the marginal abatement cost, we divided the monetized welfare change resulting from an additional 1% of reductions by the number of tons of CO_2 comprising that additional 1%. As a result both the MWC and MAC are estimated in \$/ton CO_2.

Figure 6 shows the MWCs and the MACs for the USA, EUR, JPN, CHN, IND, and MES in 2010 for the case in which all countries do the same policy which starts in 2010. The basic result is that MWCs are not the same as the MACs and they differ in some not unexpected ways given what has been learned in previous work.

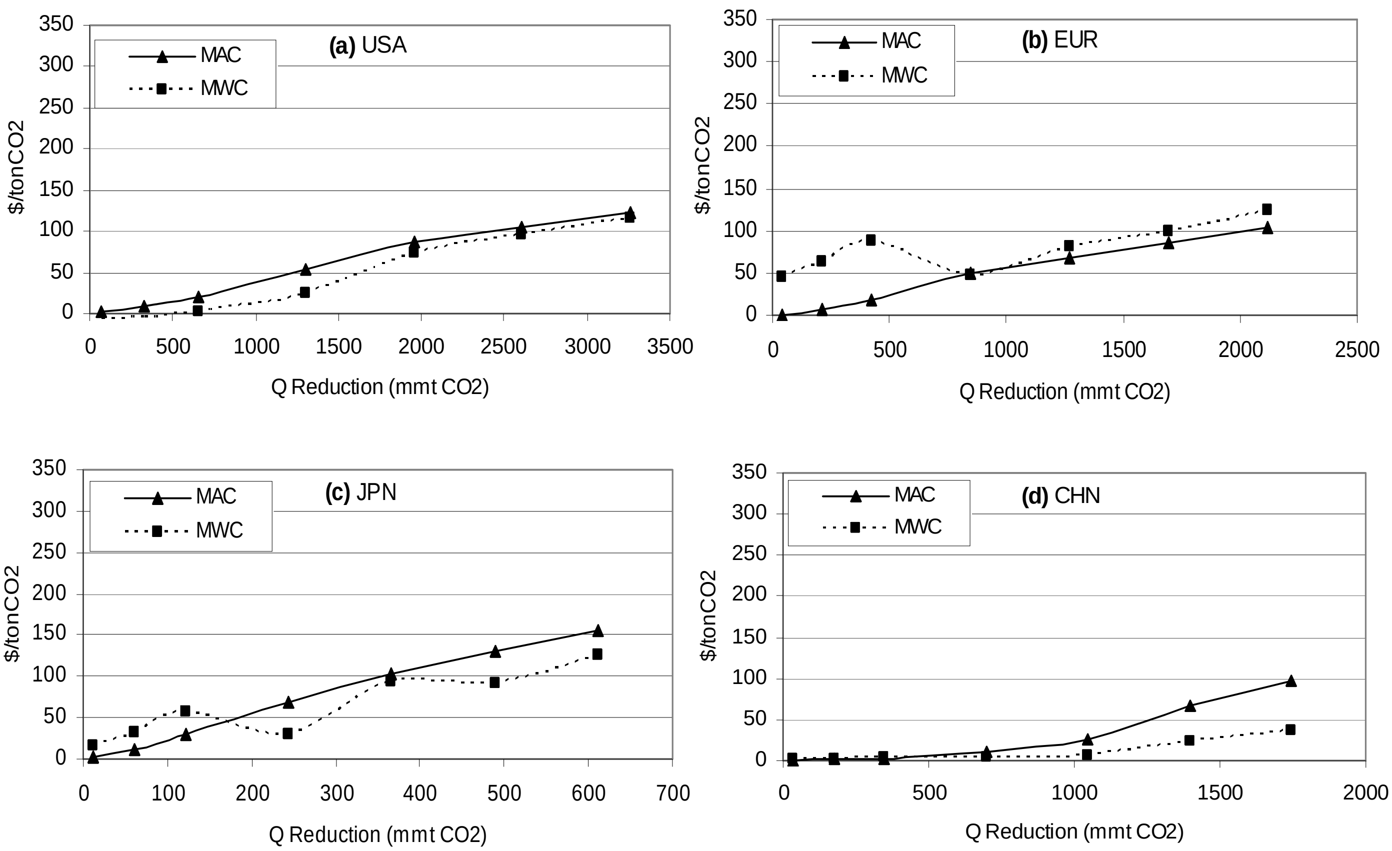

Figure 6. Marginal abatement cost curves and marginal welfare cost curves in 2010 when the reduction policy starts in 2010: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

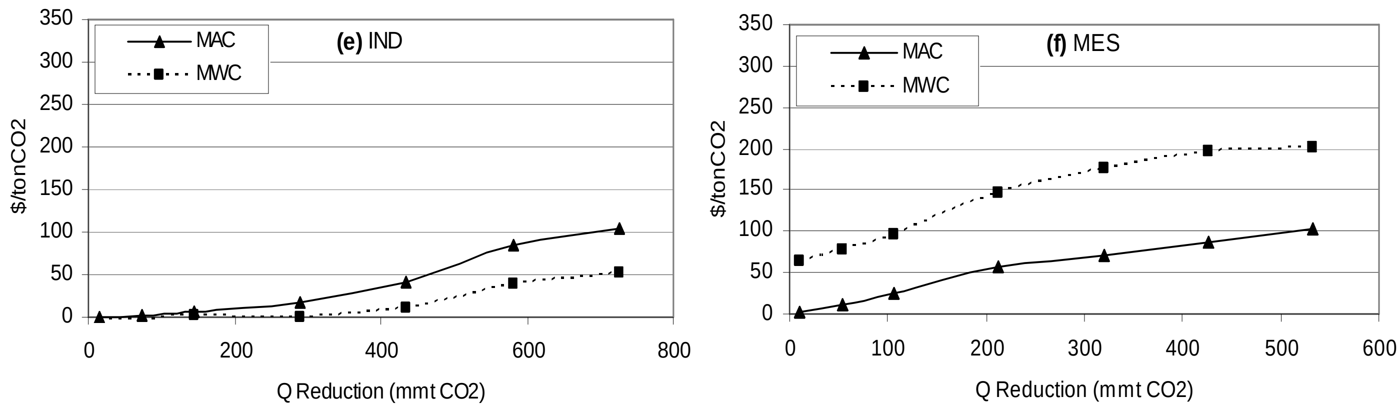

Figure 6 (cont.). Marginal abatement cost curves and marginal welfare cost curves in 2010 when the reduction policy starts in 2010: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

For example, high fuel taxes in Europe and Japan are tax distortions that are exacerbated by CO_2 policy and so the MWCs do not align very well with the MACs. The marginal deadweight loss can be many times larger than the direct cost when the CO_2 price is low and so we see especially at lower levels of abatement that the MWC is quite high compared with the MAC. The USA has few such taxes and MWC matches the MAC more closely. For the USA, we often see terms of trade benefits through the oil market and so it is not surprising that we see the MWC to be somewhat below the MAC. Terms of trade benefits through energy markets also likely contribute to lower MWC for other regions that are net importers. For MES we see the opposite—as a large energy exporter MES faces terms of trade losses that lead to MWS being far above the MAC.

Figure 7 shows the same cases but in 2050. We see that the MWCs are very different from the MACs. Welfare levels in 2050 are affected by the policy in 2050 directly (through marginal abatement costs), indirectly through terms of trade and interaction with distortions, and, in addition, by previous year policies through effects on GDP, savings, and investment. Thus it is not surprising that the marginal welfare cost in 2050 bears little resemblance to the MAC. Starting the policy in 2050 eliminates the GDP, savings, and investment effects from previous years and the difference between the MWC and MAC curves decreases significantly, as shown in **Figure 8**. Much of the very different MWC behavior in 2050 in Figure 7 can thus be explained as the residual welfare effects of policies in prior years. After adjusting for those residual effects by beginning the policy in the year examined, the MWC and MAC are more similar, but are still not equal. Notice the welfare gains in Figure 8 in CHN and IND, and for small reductions in the US. These countries rely heavily on coal, making fuel switching an effective and relatively low cost abatement options. Thus, positive terms of trade effects can be larger than the direct costs.

It is also the case that Heckscher-Ohlin markets (oil and biofuels in EPPA) can generate large swings in imports and exports as CO_2 prices change. A country may be an importer of oil at one set of CO_2 prices and import little or none at another. Biofuels become competitive at some CO_2

prices and depending on comparative advantage some countries will be importers and others exporters. Changing import and export status or big changes in what is imported or exported can then easily flip the sign of the terms of trade impacts as CO_2 prices change. Paltsev *et al.*, (2008) examined some of these effects in more detail for a specific policy finding, for example, that at an intermediate level of abatement the US would continue to import oil and so policies abroad

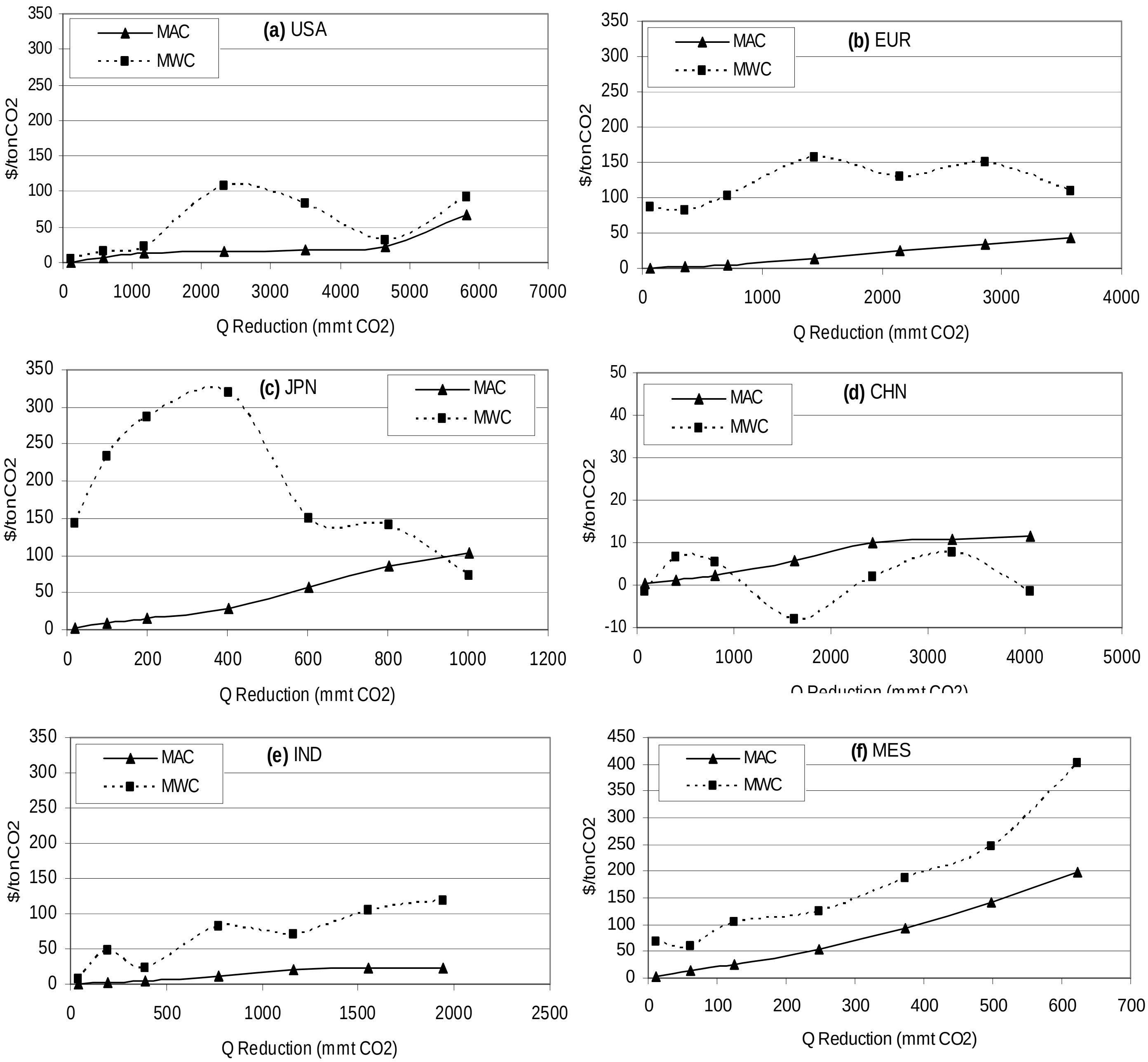

Figure 7. Marginal abatement cost curves and marginal welfare cost curves in 2050 when the reduction policy starts in 2010: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

that reduced the price of oil would result in terms of trade benefits. However, at a greater level of abatement transportation needs were met by biofuels, greatly reducing or even eliminating oil imports. With little or no imports the price of petroleum is much less relevant to the US terms of trade. But the US was then importing significant amounts of biofuels from the tropics. As a result, other countries' policies that lead them to use biofuels lead to terms of trade losses in the biofuels market because of higher prices for this now-large import. An Armington formulation of trade does not necessarily preclude such movements, but swings occur much more gradually.

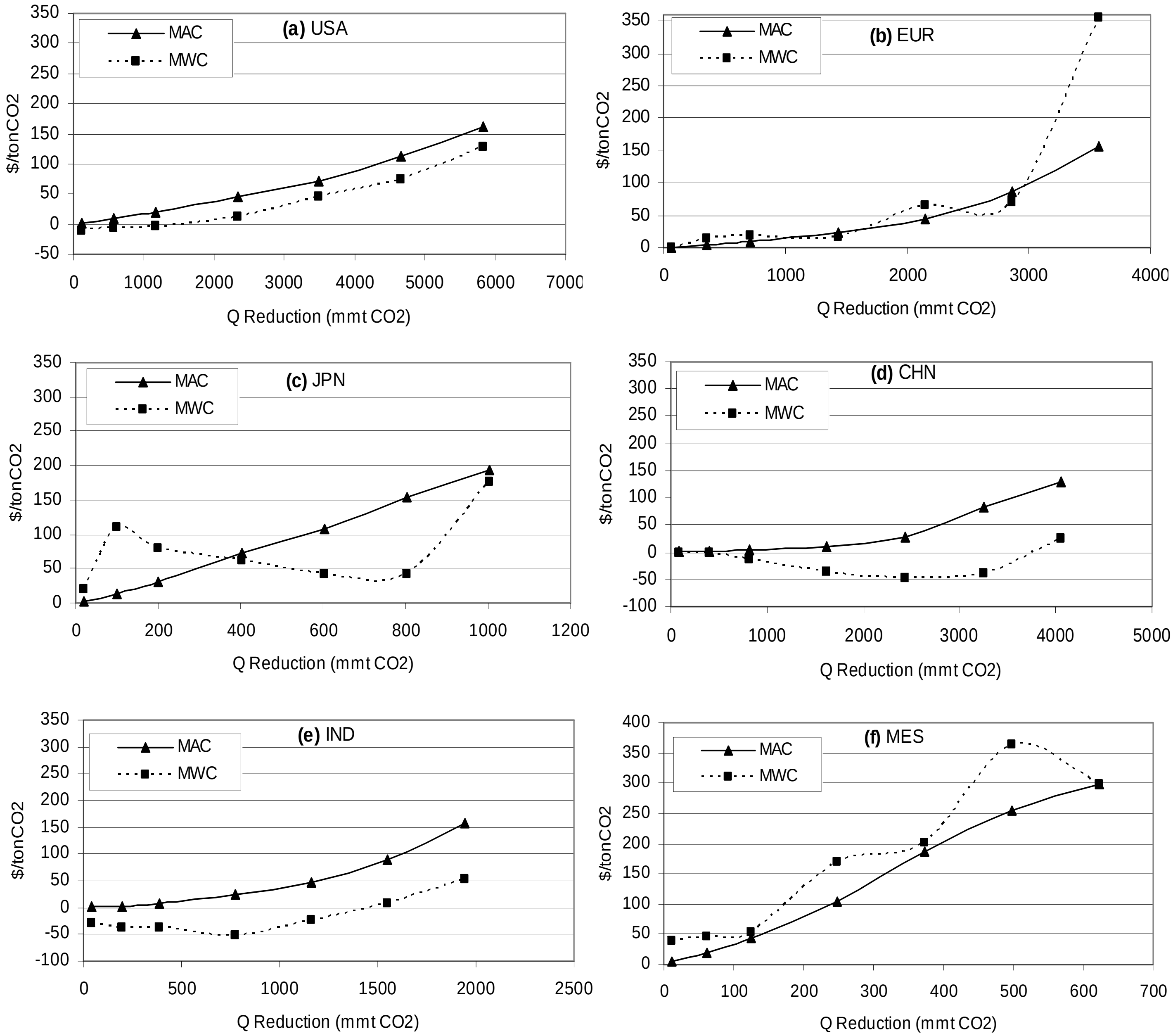

Figure 8. Marginal abatement cost curves and marginal welfare cost curves in 2050 when the reduction policy starts in 2050: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

In general, the existence of strong shifts in the magnitude and sign of the indirect welfare effects—such as strong tax interactions effects at low levels of abatement, and then possibly large terms of trade benefits at one point and large terms of trade losses at another—likely explains the roller coaster shape of the MWC curves that persist for some regions even for those 2050 MAC curve constructions that have no pre-2050 policies. As discussed earlier, when the relationship between abatement levels and marginal welfare or abatement cost clearly contains inflection points one would like a much denser sampling of points if one wanted an accurate representation of the exact shape of the curve. The goal here is simply to visually demonstrate that, however one might fill in between the points we have simulated, it is clear that there are large differences between the MAC and the MWC.

Our general conclusion is that MWC and MAC curve comparison confirms a substantial body of literature that has shown welfare results from CGE models that can not easily be explained by the CO_2 price. With a relatively simple CGE model—a static one period setting, no tax distortions, a small open economy/and or no consideration of policies abroad—one might expect to see a close relationship between the MWC and MAC. But once in a dynamic setting with changing policies abroad, trade effects, and existing tax distortions, it is not surprising that there is little correspondence. While this result is discomforting for MAC-based analysis, at the same time it offers little comfort for CGE analysis. It is unlikely that we could ever hope to accurately represent all of the various tax and other distortions in an economy, yet these results show that interactions with such distortions can dominate estimates of welfare changes. The analysis thus is general caution about over-interpreting welfare results in a world that is obviously not the idealized one of neoclassical economics.

5.3 Other GHGs

When Ellerman and Decaux and Klepper and Peterson completed their work many modeling exercises had not formally introduced the non-CO_2 GHGs. Modeling of the non-CO_2 GHGs has advanced and policy discussions have also recognized the importance of including them. We therefore constructed MACs for policies aimed at all GHGs, allowing trading among them at their Global Warming Potential (GWP) weights. We apply the policy in which all countries pursue the same reductions in all years starting in 2010 to all GHGs to create the MACs in **Figure 9**, which are compared with the MACs from the CO_2-only policy.

The inclusion of all GHGs expands abatement opportunities especially at low marginal abatement costs. Many non-CO_2 gases offer relatively inexpensive abatement opportunities, especially when one considers their high GWPs. These opportunities create a low shallow slope in the initial part of the MAC, essentially shifting the MAC outward. Once the non-CO_2 gases are mostly controlled, no more abatement opportunities exist for them and the remainder of the curve involves mostly CO_2 reductions.

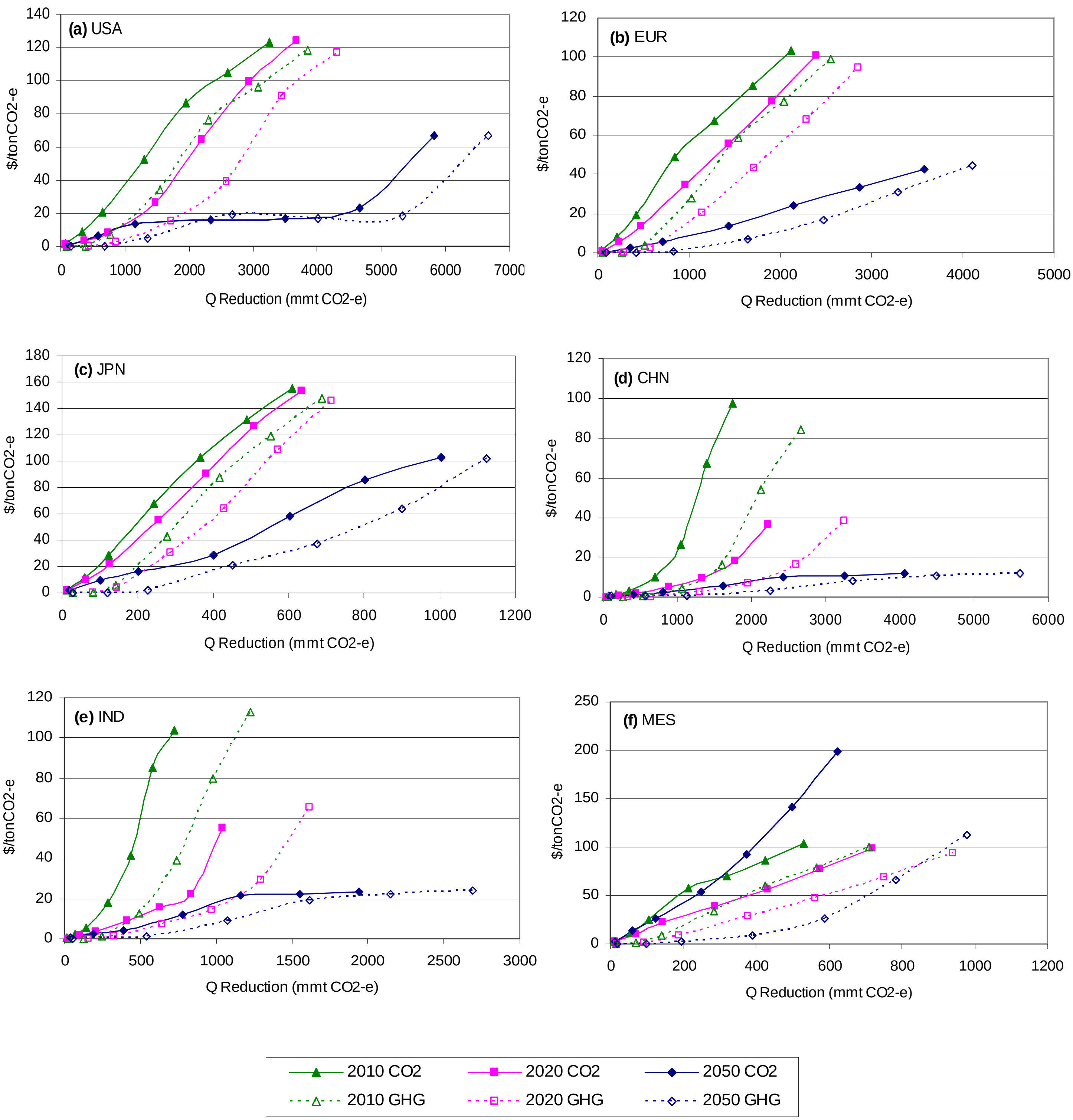

Figure 9. MACs in 2010, 2020, and 2050 when the policy started in 2010 applies to just CO_2 and when it applies to all GHGs: (a) USA, (b) EUR, (c) JPN, (d) CHN, (e) IND, and (f) MES.

6. IF YOU MUST HAVE MAC CURVES

In this section we make a best attempt to estimate MACs under the type of conditions that are relevant to existing policy discussions. We present graphs for an example set of regions for 2020 and 2050 here and provide data for all EPPA regions for 2010, 2020, and 2050 in an Appendix. The MACs were simulated to include all GHGs trading at GWP weights. The path dependency issue means we must consider carefully the policy environment over the full time horizon. The international policy environment is also of some importance. We thus follow the reduction path for the developed and developing world previously detailed in Table 4. This path involves gradual tightening of the policy over time with reductions delayed in the developing countries. Each country's MAC is estimated separately, with other countries at the Table 4 level in that year and prior years. Constructing the 2020 MACs holds in place the 2010 and 2015 policy as described in Table 4 and simulates the model for each MAC point in 2020 for each country. To construct the 2050 MAC we hold in place the 2010-2045 policies and simulate the model for each MAC point in 2050, again for each country separately.

The graphed MAC data are shown for several example countries in **Figure 10**. We illustrate them in two sections, one section with a heavy line and one with a lighter line. The different line weights are used to convey the idea that, given the construction approach, some parts of the MAC are more relevant than others for the year being considered. The lower parts of the MACs are shaded more heavily in early years. It seems less likely that a country would switch from a mild or no policy in 2015, to a 40 or 50% cut in 2020. A more realistic estimate of the cost of large cuts in 2020 should probably be simulated assuming deeper cuts in 2010 and 2015. Conversely, in 2050, after pursuing a steadily tightening policy for a number of years, it seems unlikely that a country would reverse course and suddenly switch to a low level of reduction. For example, with a 35% reduction in 2045 it seems unlikely that a country would then drop to a 1, 5, 10, or even 20% reduction in 2050.

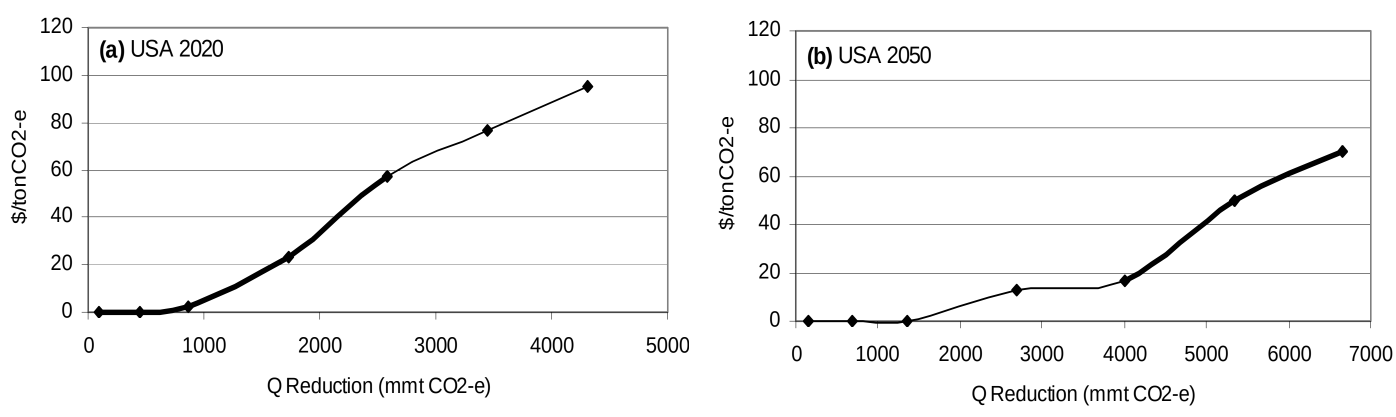

Figure 10. More realistic MACs for 2020 and 2050. Points represent 1, 5, 10, 20, 30, 40, and 50% reductions: (a) USA 2020, (b) USA 2050, (c) EUR 2020, (d) EUR 2050, (e) JPN 2020, (f) JPN 2050, (g) CHN 2020, (h) CHN 2050, (i) IND 2020, (j) IND 2050, (k) MES 2020, and (l) MES 2050.

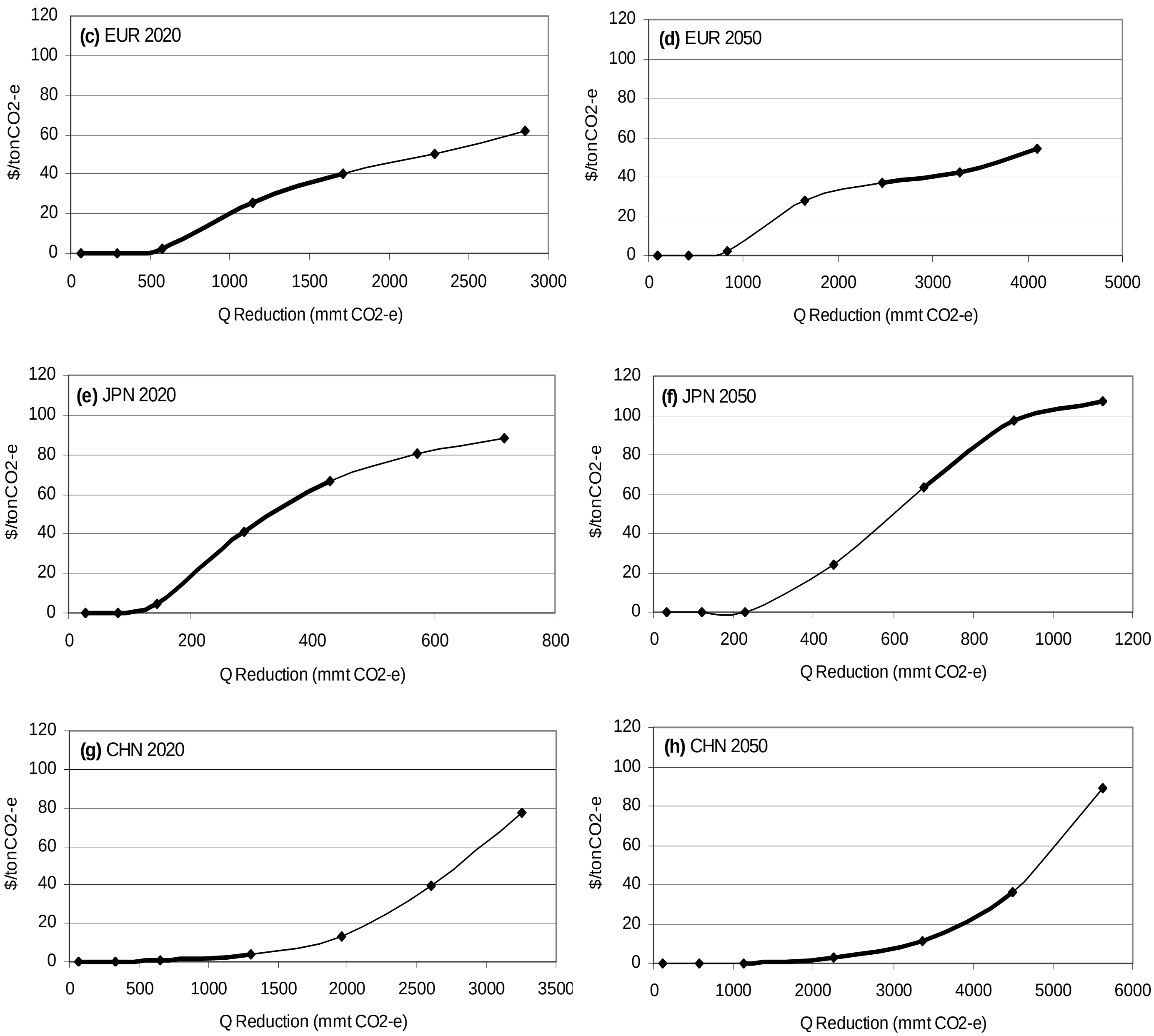

Figure 10 (cont.). More realistic MACs for 2020 and 2050. Points represent 1, 5, 10, 20, 30, 40, and 50% reductions: (a) USA 2020, (b) USA 2050, (c) EUR 2020, (d) EUR 2050, (e) JPN 2020, (f) JPN 2050, (g) CHN 2020, (h) CHN 2050, (i) IND 2020, (j) IND 2050, (k) MES 2020, and (l) MES 2050.

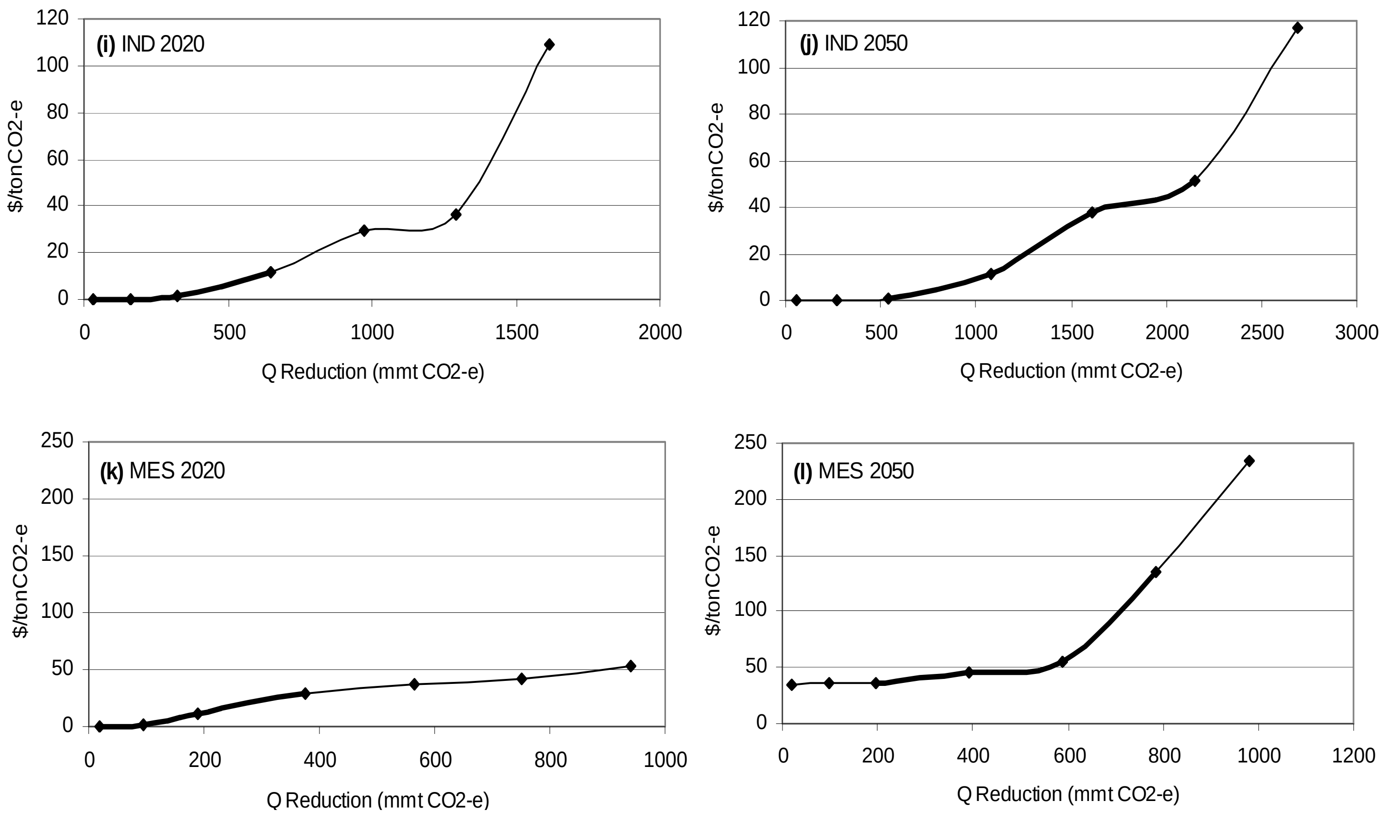

Figure 10 (cont.). More realistic MACs for 2020 and 2050. Points represent 1, 5, 10, 20, 30, 40, and 50% reductions: (a) USA 2020, (b) USA 2050, (c) EUR 2020, (d) EUR 2050, (e) JPN 2020, (f) JPN 2050, (g) CHN 2020, (h) CHN 2050, (i) IND 2020, (j) IND 2050, (k) MES 2020, and (l) MES 2050.

7. CONCLUSIONS

Many analysts have found marginal abatement cost curves to be useful devices for illustrating economic issues associated with greenhouse gas abatement. As pedagogic tools they follow in a long tradition in economics of using graphical analysis of supply and demand curves to represent markets for normal goods. In many applications the use of MACs has gone well beyond pedagogy. They have been used as the basis for reduced-form models to help illustrate likely CO_2 prices, emissions trading, and welfare costs of different abatement levels. For such purposes one would like to have some confidence that a MAC-based analysis would provide the same result as the parent model from which it was derived. Early analyses of MACs under relatively limited conditions suggested a somewhat surprising robustness. The specific test of robustness was whether a MAC in one country was affected by the level of the policy in another country. If the MAC is affected by the level of policy elsewhere and the intention is to examine emissions trading when the level of abatement in other countries is changing in the analysis, then an unstable MAC would clearly create inaccuracy in the results. Later work formulated the test of robustness somewhat differently and found more instability in the MAC. Essentially, policies abroad create a shift in the baseline for a country through changes in prices in energy markets. If this shift is taken into account in the construction of the MAC, as the earlier analysis did, then the MAC appears stable. If, however, this shift is not accounted for then the MAC shifts, and, especially at low levels of CO_2 prices, this can lead to very large errors (in percentage terms) in predicted CO_2 prices.

Is there a best practice in how to construct MACs? We argue that depends on how the MAC is to be used. Whether, for example, the baseline change from policy abroad is explicitly (or implicitly) taken into account will determine which of the approaches to MAC construction is more accurate. One approach to constructing MACs is to simulate different levels of abatement in all countries at the same time. This approach introduces the baseline shift into the MAC of each country by gradually changing the MAC slope at higher CO_2 prices—when no one is abating there are no energy market effects from abroad but these become bigger as the abatement level becomes stronger everywhere. This could be appropriate for some purposes—in negotiations for example, if one imagined other countries matching your offer on how much to abate, then a MAC constructed in this manner would give you an accurate measure of the CO_2 price you could expect in your country. In general, however, the baseline shift will introduce some inaccuracy, and earlier analysis that demonstrated stability did so under a special case that may not be appropriate to the many uses to which MACs have been applied.

Given how MACs have come to be used, the robustness of MACs in one country to changes in policy in another, is a relatively limited test. We also investigated their stability over time and whether there was path dependence—the extent to which a MAC in later years depended on the abatement level in earlier years. We examined the relationship of the MAC to Marginal Welfare Cost (MWC) and we extended MACs to include non-CO_2 GHGs. In general these investigations revealed far greater inaccuracies and instabilities in MACs than the single period analysis of impacts of abatement in other countries. These findings suggest caution in applying MACs other than for the simplest of illustrations.

With regard to stability over time, MACs, at least those derived from the parent model we used, changed greatly from period to period. If this were solely the result of changing technological opportunities over time then a set of MACs could be generated to represent each time period. However, we found strong path dependence—MACs in later years were strongly affected by the level of abatement simulated in earlier years. Thus, MAC analyses that consider dynamics of abatement—banking and borrowing—must be considered suspect.

Given a variety of previous analyses comparing welfare derived from CGE models to measures of welfare derived from a MAC analysis, we expected MACs to be a poor indicator of MWC. What was surprising was how little correspondence there was between the MAC and the MWC. MWC was far above the MAC for some regions and far below for others, and the relationship could change substantially over the range of CO_2 costs represented in the MAC. MWCs were particularly sensitive to policies in previous years. Upon reflection this result is not too surprising since saving and investment as it is affected by policies in earlier years will obviously carry over to affect welfare in later years as a completely separate influence from any mitigation policy in the later year. Extending the MACs to include other GHGs also substantially changed the shape of the MAC, lowering the slope of the MAC at low CO_2 prices.

Many analysts have used MACs. They offer an easy to understand visualization of how costs depend on the level of abatement. Unfortunately, unless one takes great care in understanding the exact conditions under which MACs are constructed and constructs them for the specific use in mind, it is very easy to misuse them. By misuse we mean exercising MACs under conditions where the results they provide would differ substantially from the result one would get from running the parent model. There are of course great uncertainties in estimating costs, and different parent models will yield very different results, and so perhaps the errors introduced by using simplified MACs are swamped by differences among the more complex models anyway. However, we can trace these differences to specific structural considerations and feedbacks in the parent model, and once one is aware of these processes and can model them, it seems a mistake to simply ignore these effects to avoid running the parent model. Nevertheless, we present in the final section of the paper, and in an Appendix, data derived from our EPPA model for each region for specific years (2010, 2020, and 2050) derived under a specific set of assumptions about how policy will evolve over that time that can be the basis of MAC construction. In developing the data with an eye toward the possible evolution of policy over the next few decades—or at least the types of policy paths that are being investigated as we write this report—it may provide a rough indication of potential abatement costs if used carefully.

Acknowledgements
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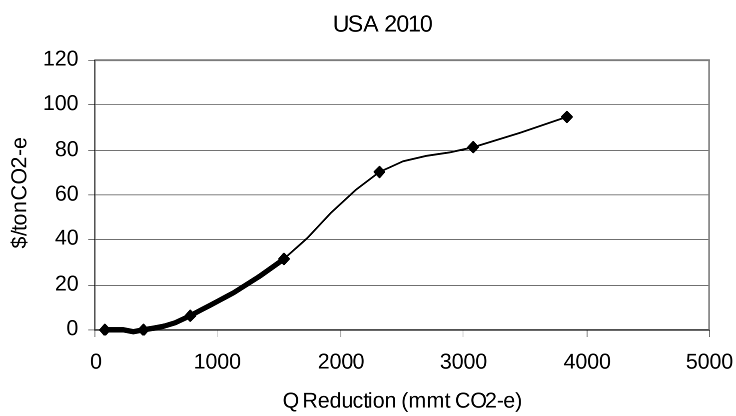
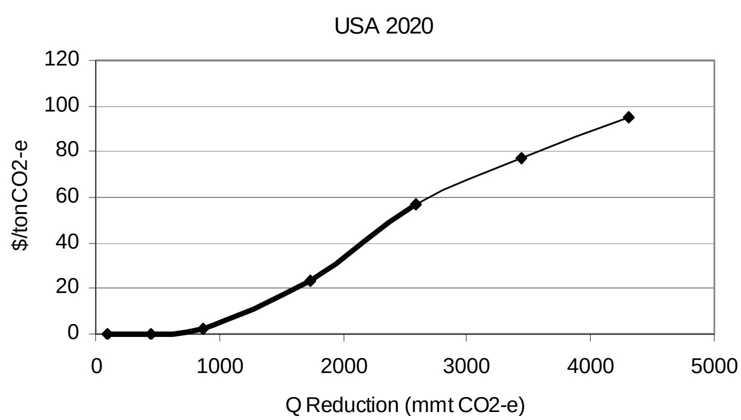
APPENDIX: Regional MACs

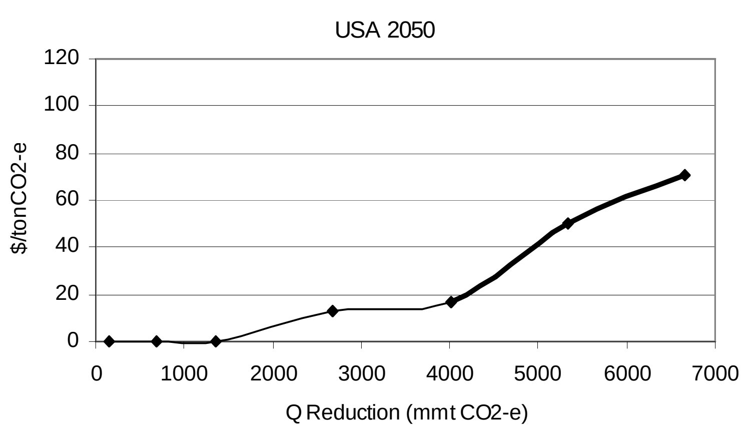
This Appendix provides the MAC data for all EPPA regions for 2010, 2020, and 2050. As in Section 6 and Figure 10, the country for which the MAC is constructed is assumed to pursue either the Annex 1 or Annex 2 path detailed in Table 4 until 2050 when it does either 1, 5, 10, 20, 30, 40, or 50% reductions. All other countries pursue the reductions specified in Table 4 for all periods. The MACs include all GHGs trading at GWP weights within the region, and do not allow international emissions trading. All marginal costs are expressed as 2005 dollars per ton of CO_2-e and the quantities of emissions reduced are in million metric tons (mmt) of CO_2-e.

United States (USA)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.00	85.54	0.02	99.11	0.22	158.05
5%	0.25	393.21	0.05	442.00	0.22	689.38
10%	6.55	775.23	2.66	869.19	0.22	1353.54
20%	31.35	1542.48	23.14	1727.75	12.95	2680.17
30%	70.52	2309.76	57.19	2586.63	16.35	4008.31
40%	81.70	3077.62	76.96	3445.97	49.79	5335.18
50%	94.61	3845.48	94.89	4305.37	70.40	6662.85

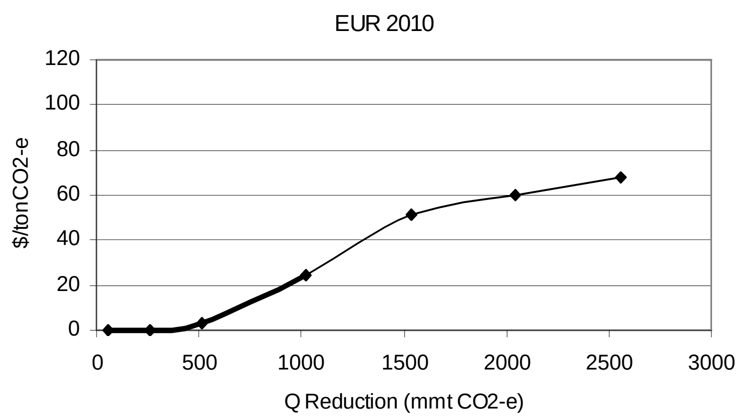


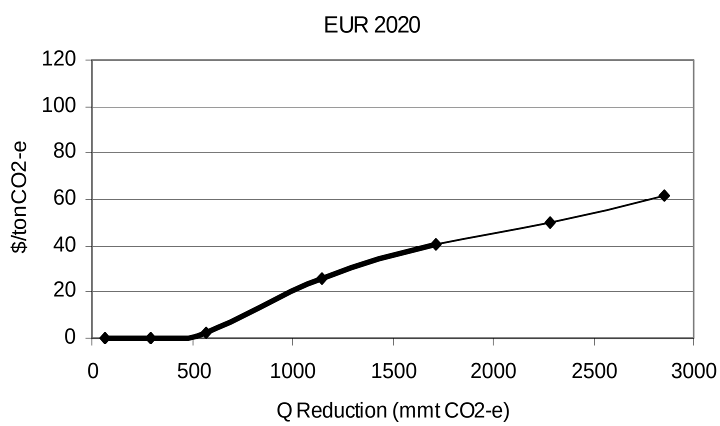


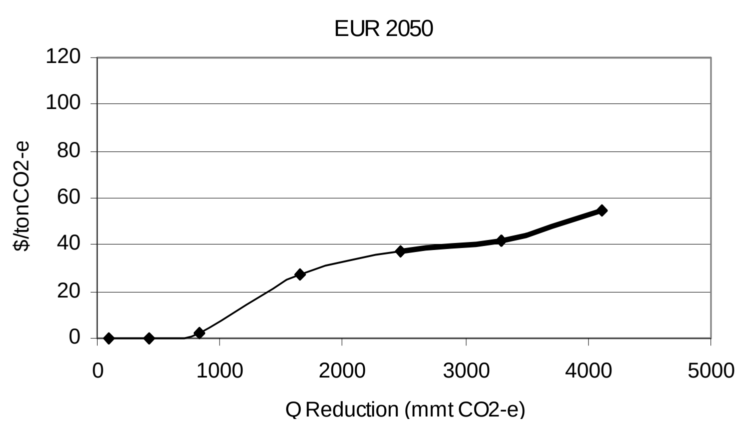


European Union+ (EUR)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.00	56.15	0.00	63.06	0.00	90.64
5%	0.04	258.69	0.01	289.39	0.00	418.71
10%	3.39	513.21	2.71	573.08	2.17	827.33
20%	24.59	1024.01	25.56	1143.07	27.65	1647.05
30%	51.38	1534.94	40.27	1713.28	36.95	2467.19
40%	59.64	2045.99	50.07	2283.54	42.12	3287.31
50%	67.92	2557.04	61.87	2853.79	54.37	4107.26

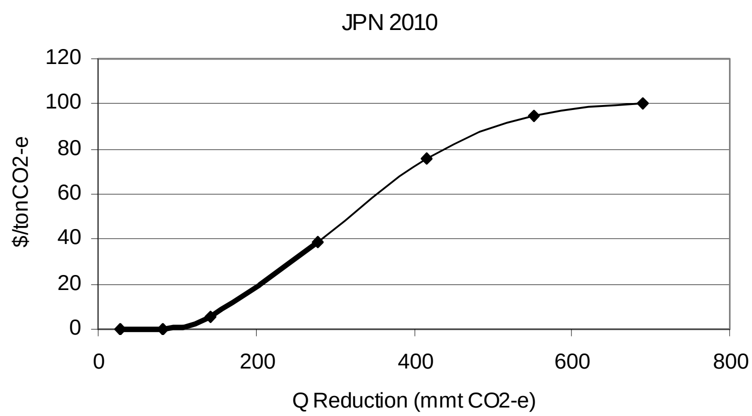


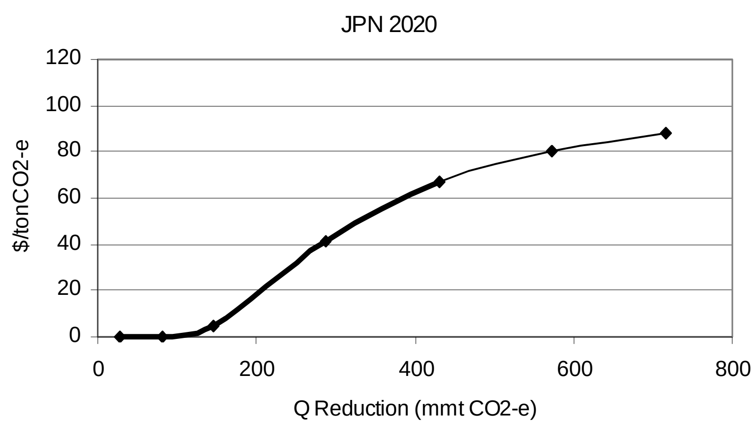


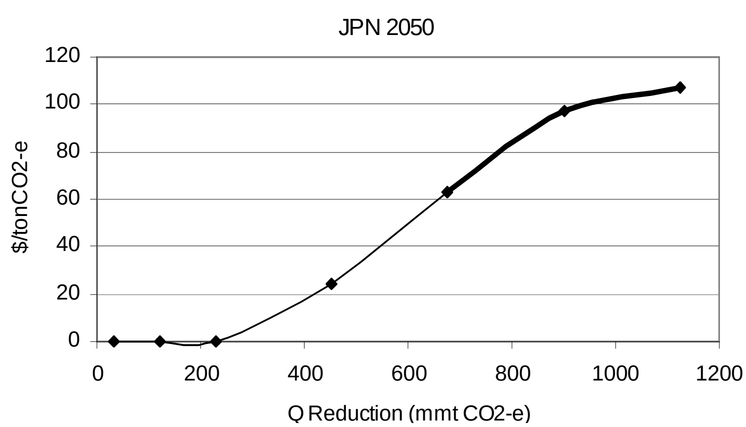


Japan (JPN)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.00	27.46	0.00	28.78	0.00	31.48
5%	0.00	81.62	0.00	81.91	0.00	121.30
10%	5.25	141.93	4.63	145.86	0.02	229.06
20%	38.59	278.77	41.28	288.19	24.23	451.76
30%	75.76	415.75	66.91	430.64	63.06	676.33
40%	94.77	552.81	80.35	573.11	97.35	900.92
50%	100.44	689.75	87.93	715.57	106.95	1125.53

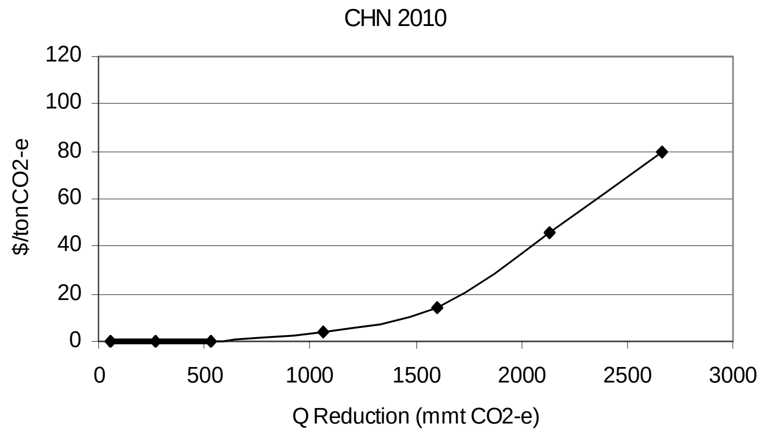


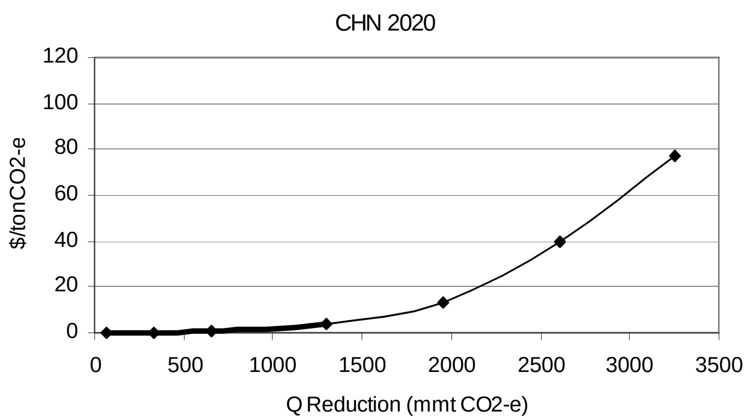


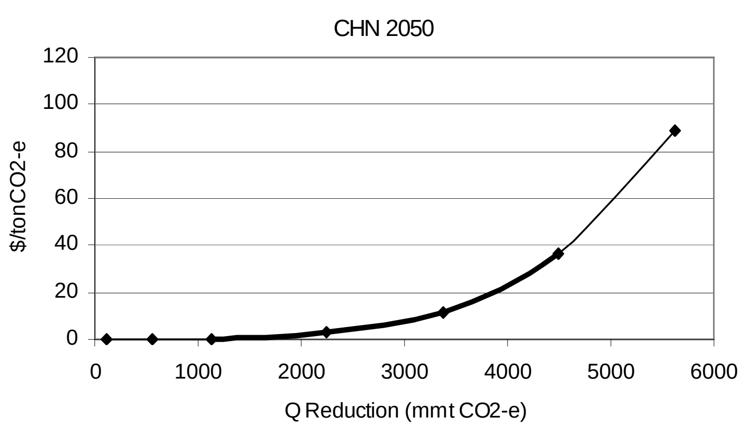


China (CHN)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.00	55.98	0.08	66.99	0.01	115.62
5%	0.02	268.49	0.14	327.30	0.02	564.60
10%	0.33	534.01	0.39	652.61	0.13	1125.66
20%	3.89	1066.17	3.80	1303.39	3.12	2248.14
30%	14.17	1598.63	12.90	1954.31	11.48	3371.12
40%	46.00	2131.04	39.57	2605.30	36.17	4494.22
50%	79.98	2663.41	77.48	3256.44	88.90	5617.31

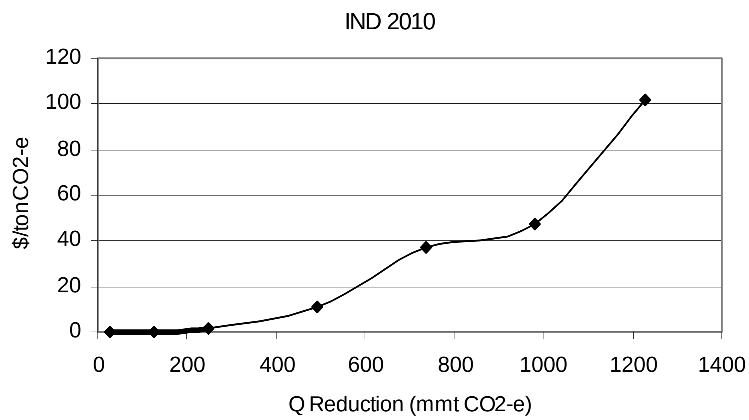


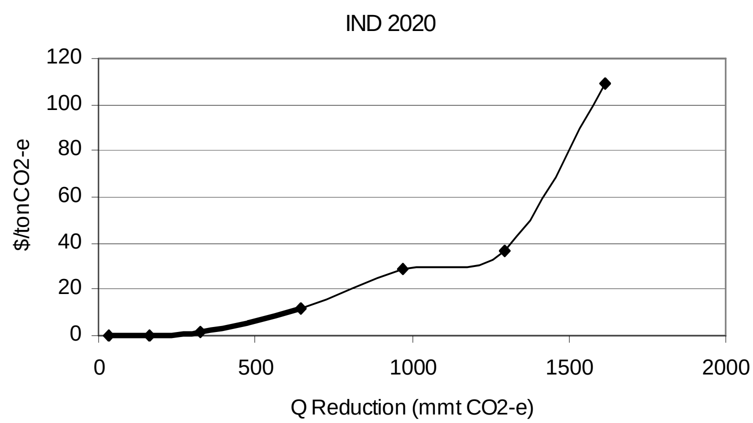


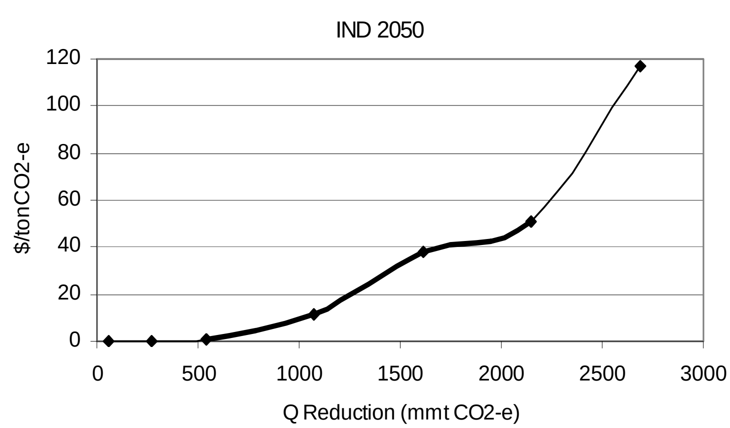


India (IND)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.00	26.32	0.00	34.53	0.00	56.77
5%	0.07	123.98	0.08	163.07	0.00	271.48
10%	1.33	246.23	1.70	324.38	0.75	538.49
20%	11.37	491.53	11.61	647.59	11.61	1075.64
30%	37.42	736.86	29.20	971.08	37.77	1613.16
40%	47.53	982.25	36.52	1294.48	50.99	2150.58
50%	101.95	1227.49	109.03	1617.71	117.01	2687.84

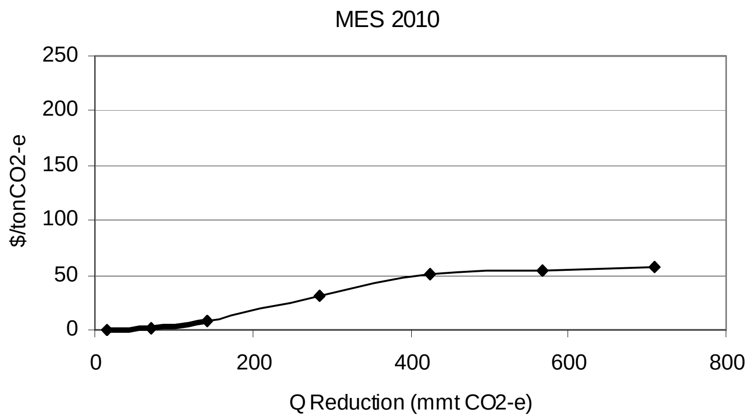


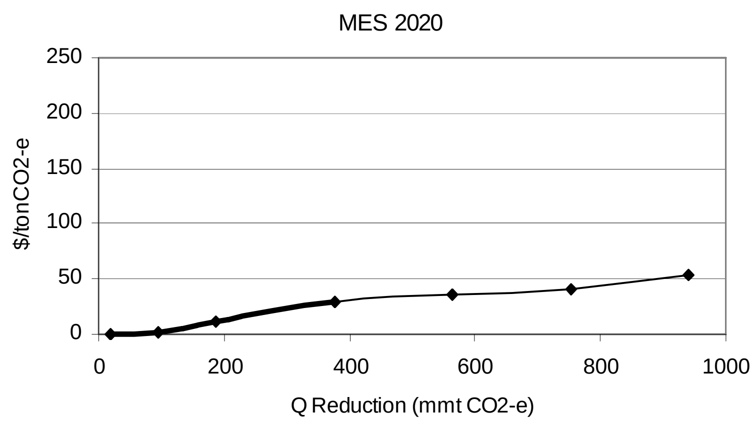


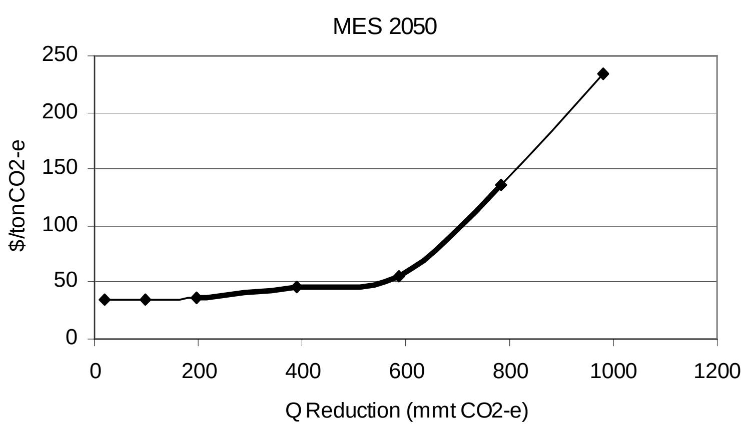


Middle East (MES)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.01	14.77	0.02	19.14	35.22	19.15
5%	0.83	71.42	2.06	94.16	35.55	97.70
10%	8.07	142.15	11.87	188.16	36.54	195.74
20%	30.79	283.91	29.61	376.08	45.37	391.62
30%	51.67	425.70	36.44	564.03	54.96	588.00
40%	53.83	567.58	41.26	752.11	135.91	783.93
50%	57.15	709.32	53.57	940.04	234.10	979.93

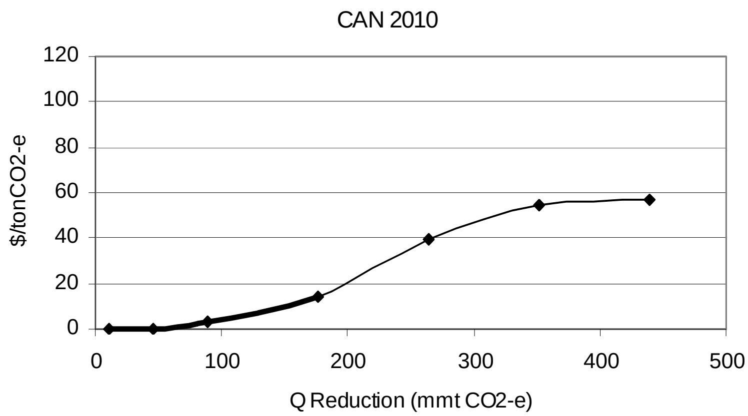


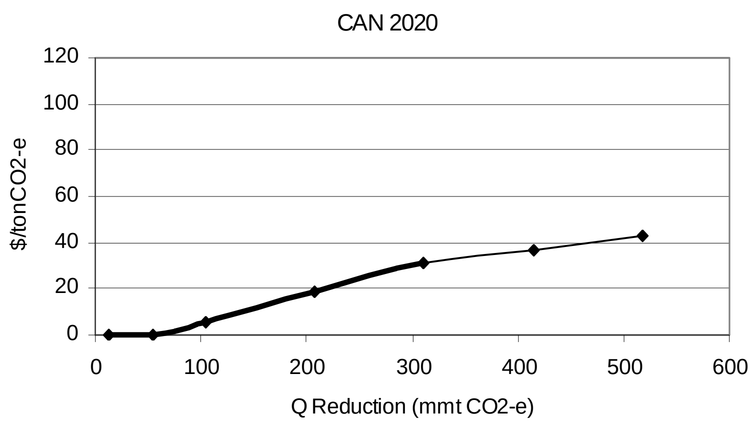


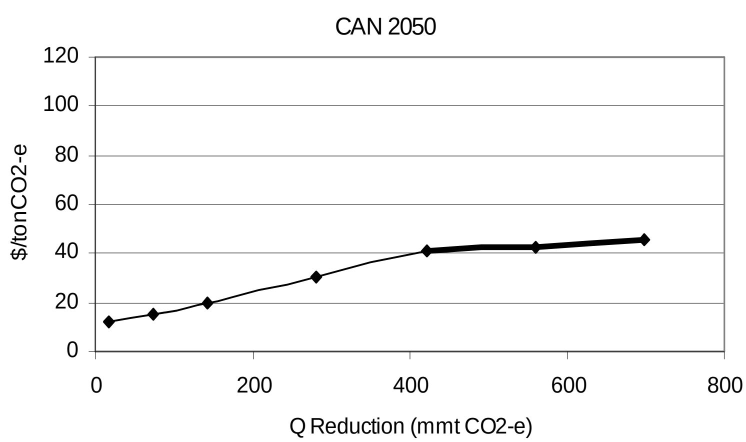


Canada (CAN)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.00	11.38	0.02	13.28	12.37	17.93
5%	0.28	45.54	0.23	54.02	14.85	73.45
10%	3.06	89.10	5.16	105.15	19.43	142.97
20%	14.31	176.78	18.98	208.11	30.68	281.75
30%	39.56	264.51	31.19	311.17	40.71	420.54
40%	54.21	352.18	36.33	414.26	42.89	559.40
50%	57.03	439.97	42.74	517.35	45.60	698.26

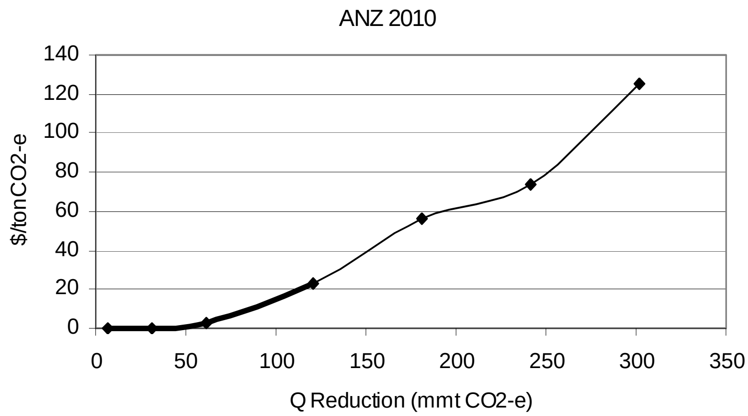


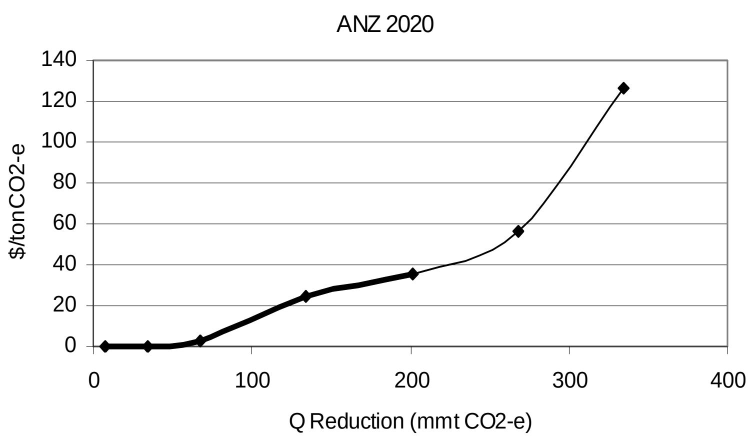


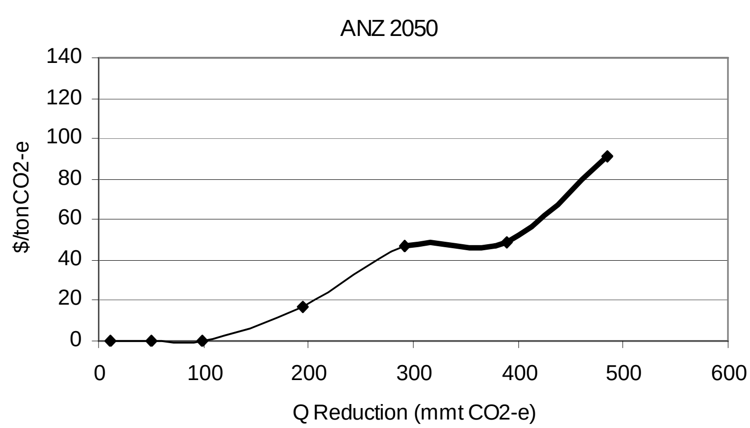


Australia and New Zealand (ANZ)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.01	6.85	0.01	7.55	0.00	11.32
5%	0.08	30.85	0.09	34.19	0.00	50.05
10%	2.35	60.92	2.48	67.67	0.16	98.33
20%	23.42	121.14	24.86	134.37	16.78	195.13
30%	56.33	181.44	35.51	201.22	46.63	291.95
40%	73.37	241.78	56.67	268.06	48.81	388.77
50%	124.84	302.02	126.39	334.74	91.02	485.37

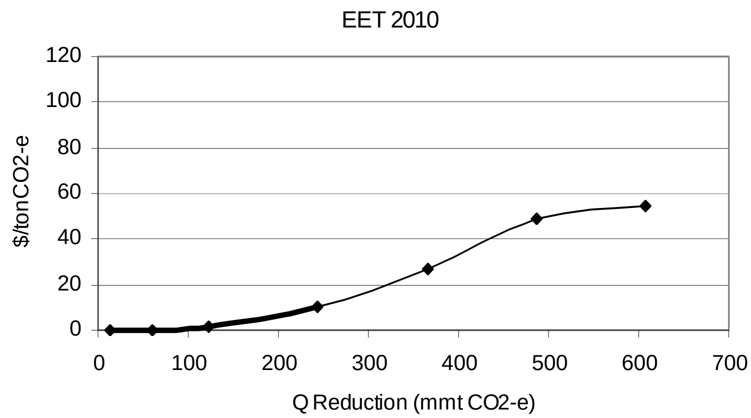


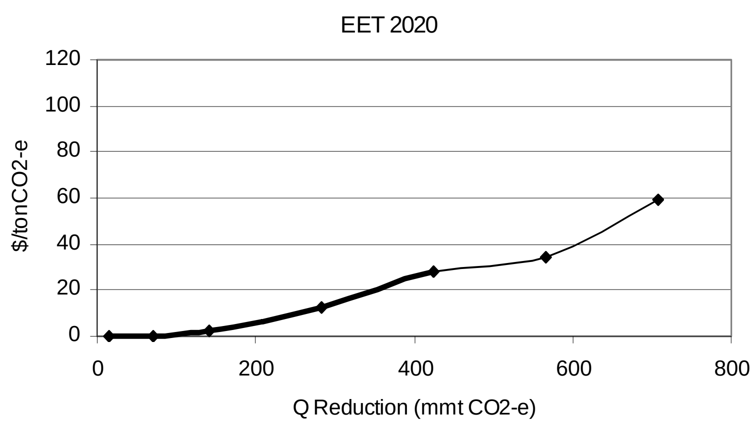


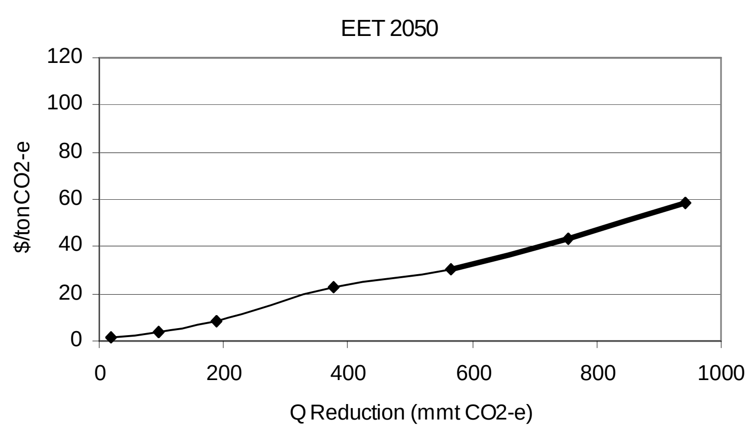


Eastern Europe (EET)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.00	12.58	0.00	14.47	1.38	19.29
5%	0.06	61.13	0.07	71.07	4.15	94.66
10%	1.43	121.93	2.12	141.77	8.73	189.03
20%	10.42	243.50	12.09	283.30	22.71	377.51
30%	26.91	365.12	28.36	424.76	30.59	566.05
40%	48.88	486.75	34.46	566.25	43.13	754.57
50%	54.74	608.40	59.03	707.72	58.54	943.23

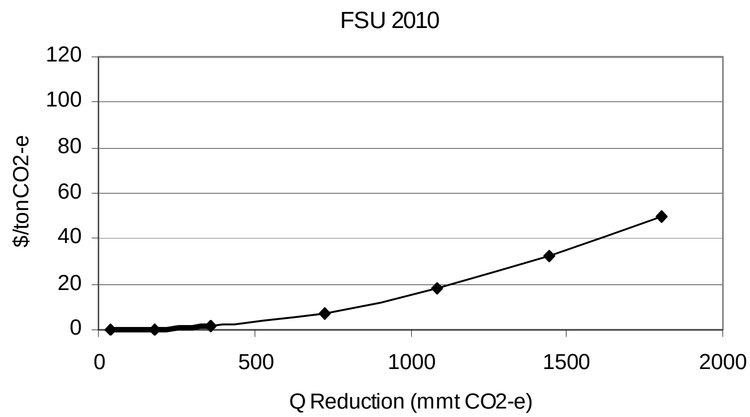


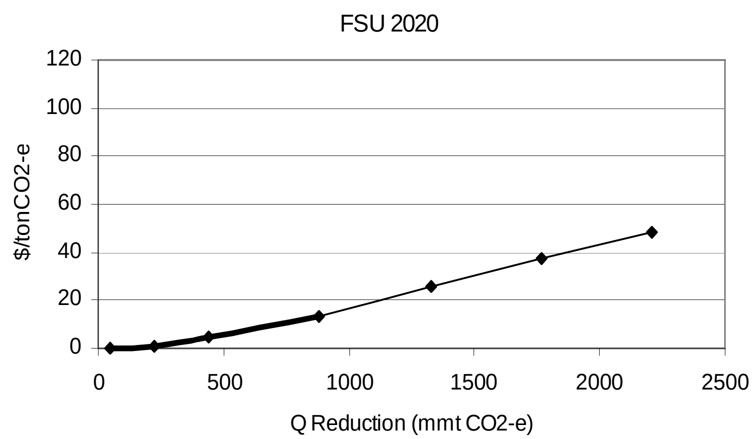


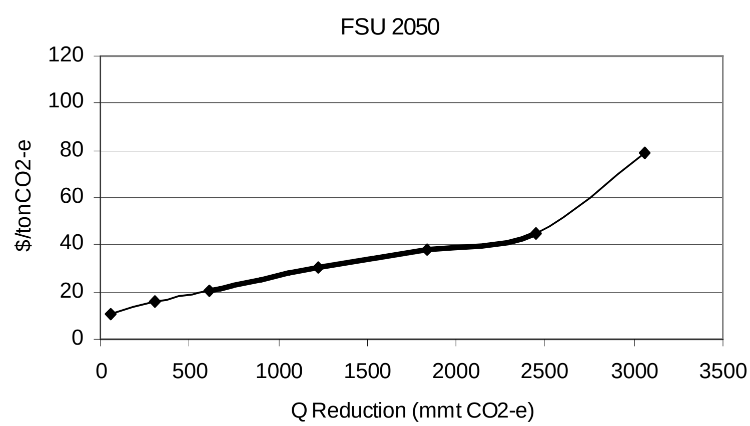


Former Soviet Union (FSU)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.01	37.47	0.02	45.30	10.32	61.68
5%	0.37	181.27	1.05	221.27	15.67	306.18
10%	1.55	361.62	4.70	442.01	20.59	611.81
20%	7.10	722.68	13.53	883.39	30.49	1223.11
30%	18.06	1083.63	25.90	1324.82	38.27	1834.42
40%	32.76	1444.76	37.51	1766.43	44.89	2445.72
50%	49.79	1805.76	48.35	2207.88	79.12	3057.01

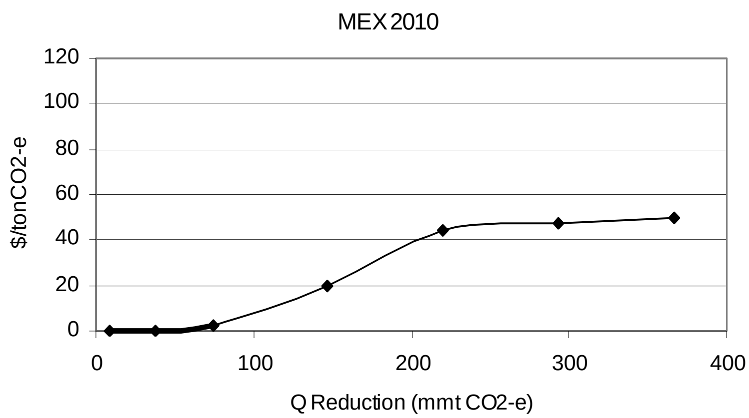


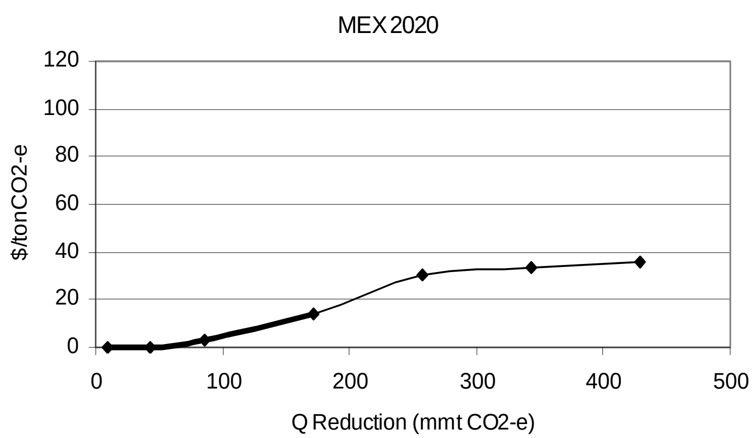


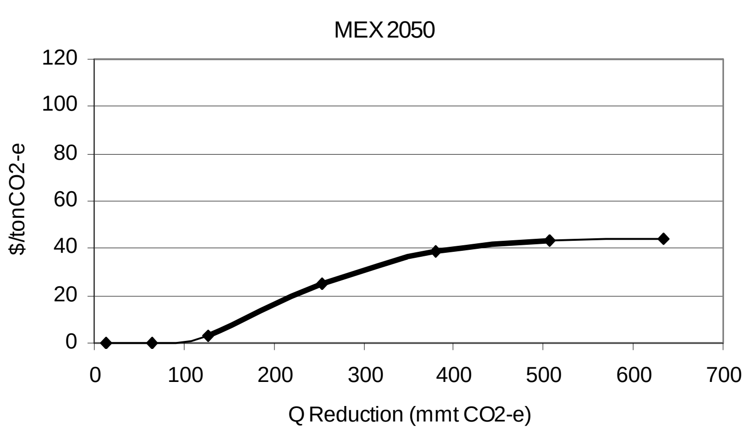


Mexico (MEX)

	2010	2010	2020	2020	2050	2050
	MAC	**Q REDUC**	**MAC**	**Q REDUC**	**MAC**	**Q REDUC**
1%	0.00	8.28	0.01	9.39	0.00	13.89
5%	0.07	37.38	0.26	43.32	0.14	64.08
10%	2.38	73.86	2.88	86.30	3.00	127.28
20%	20.06	147.14	13.75	171.90	25.19	254.16
30%	44.27	220.39	30.38	257.72	38.69	381.02
40%	47.47	293.69	33.70	343.43	42.99	507.85
50%	49.78	366.99	35.51	429.13	43.71	634.69

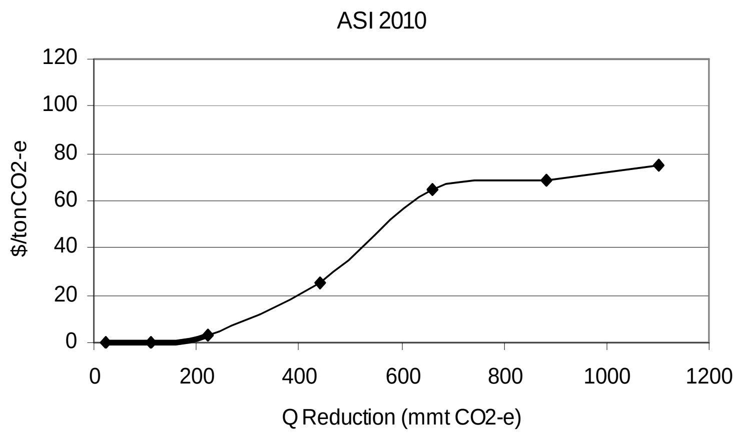


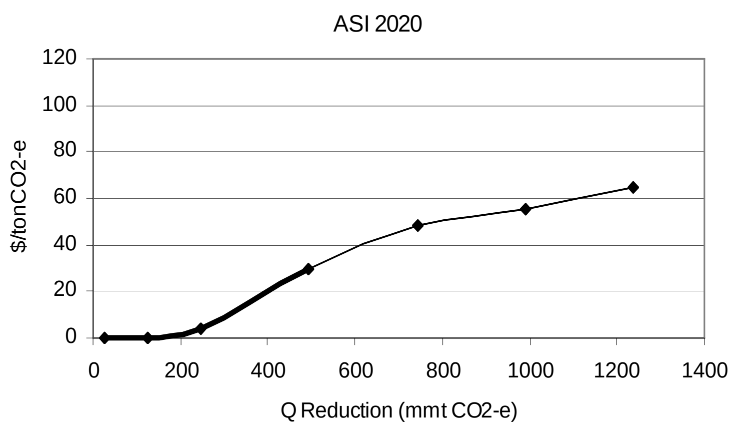


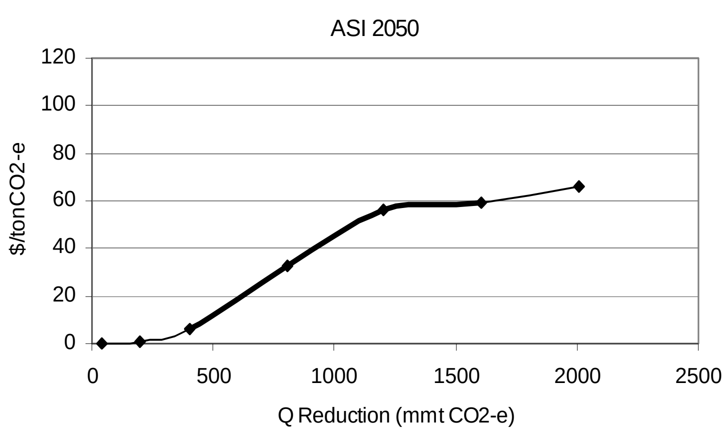


Higher Income East Asia (ASI)

	2010 MAC	2010 Q REDUC	2020 MAC	2020 Q REDUC	2050 MAC	2050 Q REDUC
1%	0.01	23.39	0.01	26.03	0.02	41.04
5%	0.10	111.11	0.16	124.45	0.44	201.38
10%	2.87	221.04	3.77	247.95	5.75	402.05
20%	25.41	441.08	29.72	495.02	32.40	803.81
30%	64.73	661.37	47.99	742.19	56.50	1205.47
40%	68.71	881.57	55.48	989.50	59.34	1607.15
50%	75.07	1101.77	64.92	1236.66	66.15	2008.90

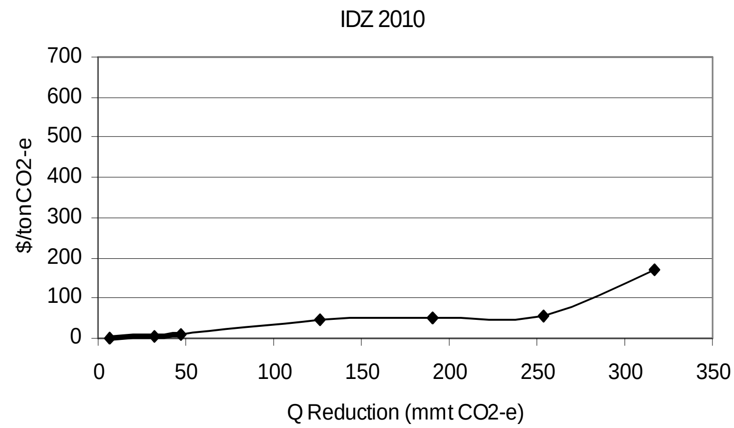


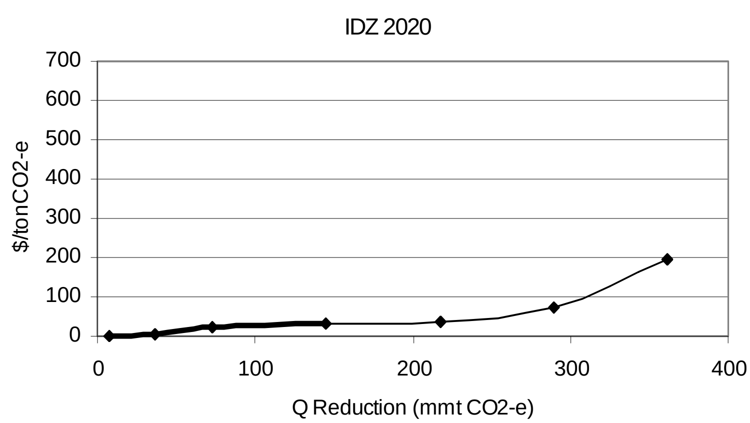


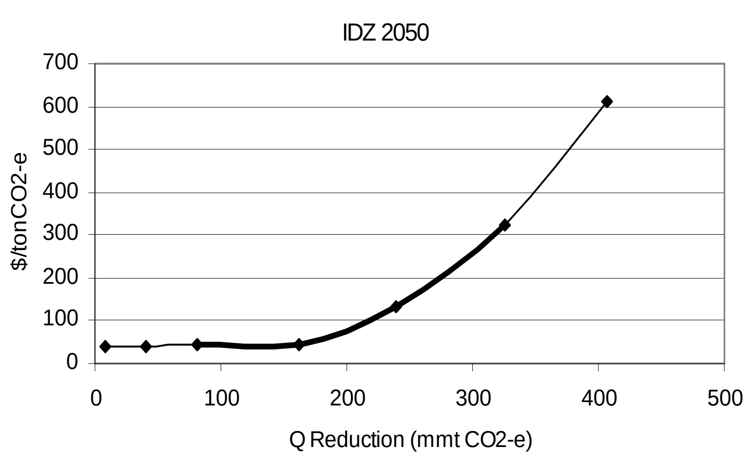


Indonesia (IDZ)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.02	6.55	0.06	7.50	39.15	8.19
5%	3.48	31.76	5.39	36.29	42.07	40.74
10%	8.89	47.47	20.67	72.46	42.39	81.44
20%	45.16	126.80	32.75	144.83	44.43	162.83
30%	49.83	190.17	36.02	217.21	133.08	239.51
40%	54.26	253.55	70.76	289.58	325.53	325.49
50%	171.34	316.88	193.47	361.92	611.54	406.83

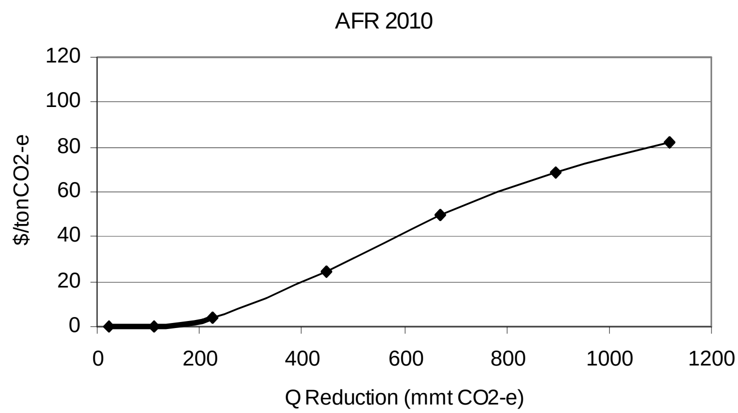


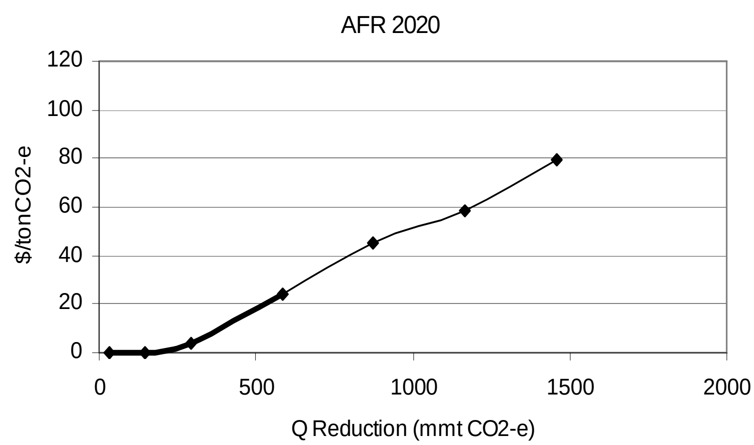


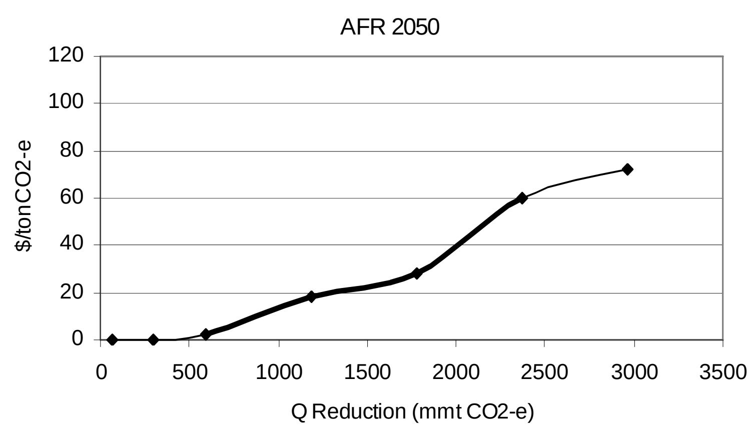


Africa (AFR)

	2010	2010	2020	2020	2050	2050
	MAC	**Q REDUC**	**MAC**	**Q REDUC**	**MAC**	**Q REDUC**
1%	0.00	23.72	0.00	30.91	0.00	63.06
5%	0.11	112.61	0.13	146.46	0.01	297.38
10%	3.66	224.07	4.00	291.71	2.36	592.26
20%	24.30	447.53	24.21	582.70	18.12	1184.29
30%	49.51	670.95	45.51	873.90	27.80	1776.44
40%	68.91	894.38	58.22	1164.97	60.03	2368.62
50%	81.99	1117.81	79.48	1456.02	72.17	2960.80

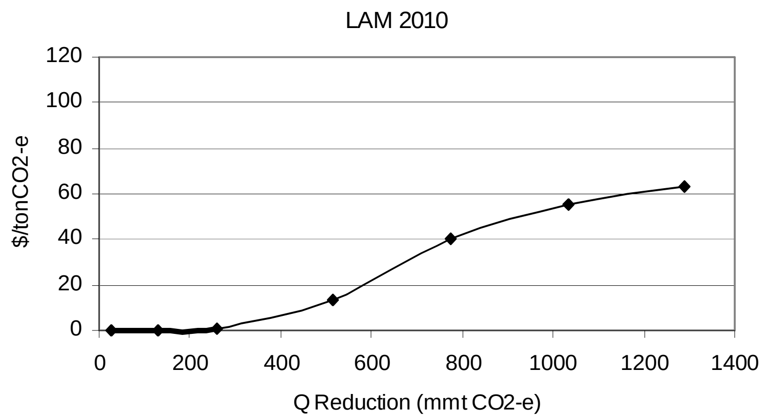


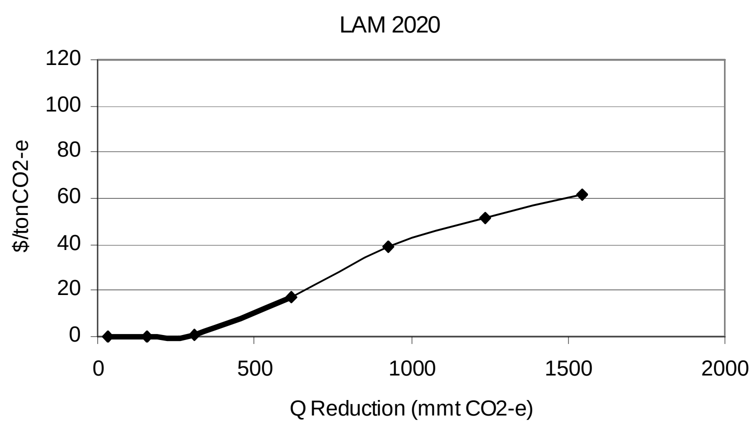


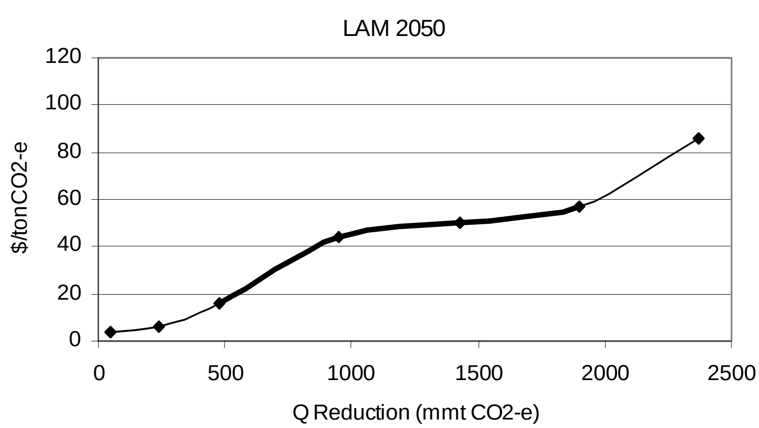


Central and South America (LAM)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.00	28.17	0.00	33.51	3.72	47.83
5%	0.03	130.53	0.03	156.22	6.22	237.66
10%	0.74	258.82	0.92	309.89	16.06	474.91
20%	13.75	516.54	17.23	618.53	43.98	949.64
30%	40.64	774.36	38.83	927.39	50.10	1424.29
40%	55.65	1032.11	51.76	1236.27	56.88	1898.95
50%	63.41	1289.85	61.52	1545.10	85.52	2373.57

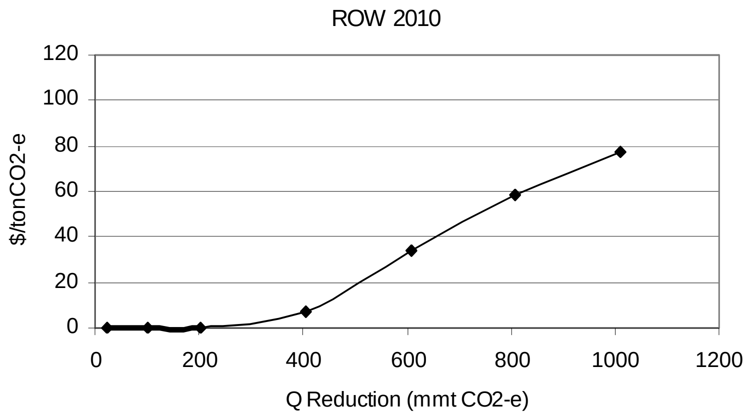


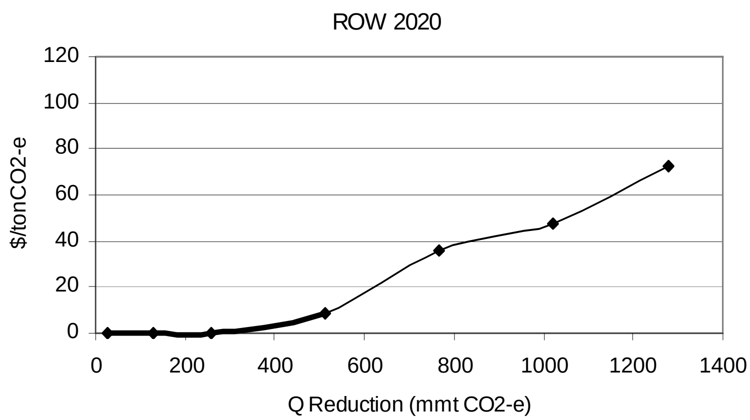


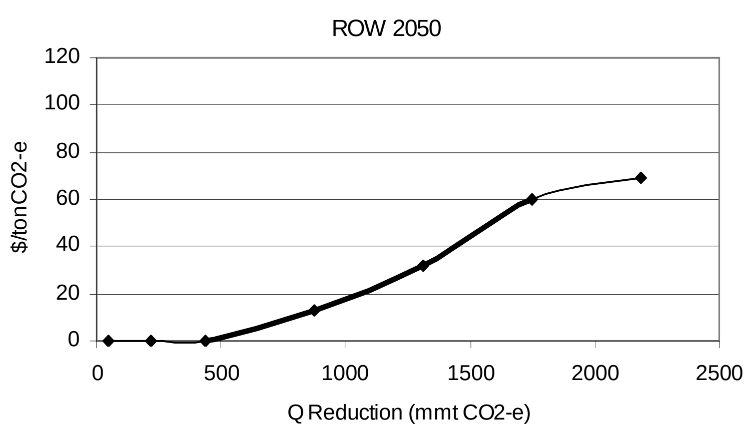


Rest of World (ROW)

	2010	2010	2020	2020	2050	2050
	MAC	Q REDUC	MAC	Q REDUC	MAC	Q REDUC
1%	0.00	21.82	0.00	27.78	0.00	46.81
5%	0.02	102.56	0.02	129.42	0.01	221.02
10%	0.14	203.16	0.17	256.62	0.23	439.16
20%	7.35	405.02	8.58	511.60	12.55	876.25
30%	34.11	607.00	36.22	766.87	31.68	1313.84
40%	58.05	809.02	47.30	1022.30	59.98	1751.44
50%	77.57	1011.05	72.39	1277.60	69.10	2189.03







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