MIT Joint Program on the Science and Policy of Global Change

Combining a Renewable Portfolio Standard with a Cap-and-Trade Policy:
A General Equilibrium Analysis

Jennifer F. Morris, John M. Reilly, and Sergey Paltsev

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Jennifer F. Morris[1], John M. Reilly and Sergey Paltsev

Abstract

Many efforts to address greenhouse gas emissions combine a cap-and-trade system with other measures such as a renewable portfolio standard. In this paper we use a computable general equilibrium (CGE) model, the MIT Emissions Prediction and Policy Analysis (EPPA) model, to investigate the effects of combining these policies. We find that adding an RPS requiring 20 percent renewables by 2020 to a cap that reduces emissions by 80% below 1990 levels by 2050 increases the net present value welfare cost of meeting such a cap by 25 percent over the life of the policy, while reducing the CO_2*-equivalent price by about 20 percent each year.*

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1. INTRODUCTION

Most economists see incentive-based measures such as a cap-and-trade system or an emissions tax as cost-effective instruments for limiting greenhouse gas (GHG) emissions (for example, Baumol and Oates, 1988; Tietenberg, 1990; Stavins, 1997; Palmer and Burtraw, 2005; Dobesova *et al.*, 2005). In actuality, many efforts to address GHG emissions combine a cap-and-trade system with regulatory instruments, such as a renewable portfolio standard (RPS). Examples include the European Union’s 20-20-20 goal and the Waxman-Markey bill (H.R. 2454) passed by the U.S. House of Representatives in 2009. Here we investigate how a renewable portfolio standard (RPS) interacts with a cap-and-trade policy.

To do this, we use a computable general equilibrium (CGE) model. An advantage of such a model is that it captures all of the interactions and ripple effects throughout the economy. We use the MIT Emissions Prediction and Policy Analysis (EPPA) model, which was developed to evaluate the impact of energy and environmental policies on global economic and energy systems, and augment it to better represent renewable electricity technologies.

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A renewable portfolio standard (also called a renewable electricity standard or RES) is a policy that requires that a minimum amount of electricity come from renewable energy sources, such as wind, solar, and biomass. Most commonly the RPS is in terms of percentage of electricity sold, as capacity- and production-based requirements do not ensure that renewable electricity is actually produced and used. The energy sources qualifying as “renewable” to meet the standard can vary. Wind, solar (solar thermal and photovoltaic), biomass, and geothermal are generally always eligible. Hydroelectricity may or may not be eligible. A commonly proposed rule is that existing hydroelectric generation does not count, but incremental new hydroelectricity does (EIA, 2007). Municipal solid waste and landfill gas are sometimes included. Some argue that the standard should be expanded to a low-carbon portfolio standard, including technologies like nuclear, coal plants with carbon capture and storage (CCS), or even, as is the case in Pennsylvania, integrated coal gasification combined cycle plants without CCS, but almost none of the existing RPS policies or proposals consider these technologies eligible.[2]

Many RPS programs utilize tradable renewable electricity certificates (RECs) to increase the flexibility and reduce the cost of meeting the target. A REC is created when a specified amount (e.g. kilowatt-hour or megawatt-hour) of renewable electricity is generated, and it can be traded separately from the underlying electricity generation. REC transactions create a second source of revenue for renewable generators, which functions like a subsidy. RECs also offer flexibility to retail suppliers by allowing them to comply by either directly purchasing renewable electricity or by purchasing RECs. Banking and borrowing of RECs may also be allowed for flexibility.

Renewables have generally not been well represented in macroeconomic models because the variability of the resource is not captured. We reformulate the representation of renewables to include the need for back-up generation capacity when the renewable resource is not available. We then develop a system that allows REC trading within the model. We then use the revised model to investigate the role and cost of an RPS requirement as part of a broader GHG reduction policy.

This paper is organized as follows: In Section 2 we describe the CGE model we use, and how we modified it to better represent renewable technologies and to implement an RPS requirement. Section 3 assesses the impacts of an RPS policy, both alone and combined with a cap-and-trade policy, and considers the sensitivity of the results to the costs and availability of generating technologies. In Section 4 we offer some conclusions.

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[2] Another RPS design option is “tiered” targets. Tiered targets establish different sets of targets and timetables for different renewable technologies (for example, one target for solar and another for wind and biomass). The purpose of tiers is to ensure that an RPS provides support to not just the least-cost renewable energy options, but also to other “preferred” resources such as solar power (DeCarolis and Keith, 2006). This design option would tend to make compliance with the target more expensive by mandating technologies other than the least-cost renewables.

2. ANALYSIS METHOD

2.1 The Emissions Prediction and Policy Analysis (EPPA) Model

The EPPA model is a multi-region, multi-sector recursive-dynamic representation of the global economy (Paltsev *et al.*, 2005). The level of aggregation of the model is presented in **Table 1**. Non-energy activities are aggregated to seven sectors, and the energy sector is modeled in more detail. All production sectors of the economy interact through a full input-output structure. The synthetic coal gas industry produces a perfect substitute for natural gas. The oil shale industry produces a perfect substitute for refined oil. Electricity generation technologies produce perfectly substitutable electricity except for renewables which are modeled as producing an imperfect substitute. The electricity generation technologies in red are new additions to the model from this work, and the basis for including this reformulation is discussed below. Biomass use is included both in electric generation and in transport where a liquid fuel is produced that is assumed to be a perfect substitute for refined oil.

Table 1. EPPA Model Details.

Country or Region[†]	***Sectors***	***Factors***
Developed	***Final Demand Sectors***	Capital
United States (USA)	Agriculture	Labor
Canada (CAN)	Services	Crude Oil Resources
Japan (JPN)	Energy-Intensive Products	Natural Gas Resources
European Union+ (EUR)	Other Industries Products	Coal Resources
Australia & New Zealand (ANZ)	Transportation	Shale Oil Resources
Former Soviet Union (FSU)	Household Transportation	Nuclear Resources
Eastern Europe (EET)	Other Household Demand	Hydro Resources
Developing	***Energy Supply & Conversion***	Wind/Solar Resources
India (IND)	Electric Generation	Land
China (CHN)	Conventional Fossil	
Indonesia (IDZ)	Hydro	
Higher Income East Asia (ASI)	Nuclear	
Mexico (MEX)	Wind, Solar	
Central & South America (LAM)	Biomass	
Middle East (MES)	Advanced Gas (NGCC)	
Africa (AFR)	Advanced Gas with CCS	
Rest of World (ROW)	Advanced Coal with CCS	
	Wind with Gas Backup	
	Wind with Biomass Backup	
	Fuels	
	Coal	
	Crude Oil, Shale Oil, Refined Oil	
	Natural Gas, Gas from Coal	
	Liquids from Biomass	
	Synthetic Gas	

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

The model includes representation of abatement of CO_2 and 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).

2.2 Representing Renewables and Renewable Policy

Renewables were represented in the EPPA model as an imperfect substitute for other electricity to reflect the intermittency of the resource and variability in supply from better and more easily accessible sites to those where the resource was less dependable and more remote. A well-known property of the constant elasticity of substitution (CES) function used is that it is share-preserving, thus tending to limit renewable penetration to not much beyond initial shares. In fact, the amount of fairly high quality wind is not a limiting factor in the U.S. The main issue is intermittency and in some cases remoteness, but this can be overcome with new transmission and either back-up capacity or through effective storage. High volume and relatively long-term battery storage is not currently practical, and even pumped hydro and compressed air energy storage appear fairly expensive. Hence we chose to represent these technologies as requiring backup capacity.

We add two new renewable backstop technologies: large scale wind with natural gas backup and large scale wind with biomass backup. They are modeled as perfect substitutes for other electricity because the backup makes up for intermittency. The additional costs for large scale wind (transmission and backup or storage) are incorporated into the costs of the new technologies. This represents in our model the real cost of the variable resource, and findings that natural gas generation capacity is crucial for the operation of a large-scale wind system (*e.g.* Decarolis and Keith, 2006). For these technologies, we follow a convention of specifying a CES production function that requires specification of cost shares of each input.

We distinguish between renewables at low penetration levels and at large scale. For low penetration rates we retain the specification of renewables as an imperfect substitute for conventional electricity (Paltsev *et al.*, 2005). This specification allows expansion of existing renewables with gradually increasing costs of integrating variable resources into the conventional grid. To represent the possibility of greater renewable penetration, we add the two new wind technologies where backup capacity is required with installation of the renewable generation capacity. The backup capacity allows the renewable source to be dispatched as needed, utilizing the backup capacity to make up for the variability of the renewable resource.

Table 2. Cost Calculation of Electricity from Various Sources.

	Units	Pulverized Coal	Solar Thermal	Solar PV	Wind	Biomass	NGCC	Wind Plus Biomass Backup [1]	Wind Plus Gas Backup [1]
"Overnight" Capital Cost	$/kW	2058	5021	6038	1923	3766	948	5689	2871
Capital Recovery Charge	%	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Fixed O&M	$/kW	27.5	56.78	11.68	30	64.5	11.7	94.5	41.7
Variable O&M	$/kWh	0.0045	0	0	0	0.0067	0.002	0.0067	0.002
Project Life	Years	20	20	20	20	20	20	20	20
Capacity Factor	%	85	35	26	35	80	85	42	42
(Capacity Factor Wind)	%							35	35
(Capacity Factor Biomass/NGCC)	%							7	7
Operating Hours	Hours	7446	3066	2277.6	3066	7008	7446	3679.2	3679.2
Capital Recovery Required	$/kWh	0.02	0.14	0.23	0.05	0.05	0.01	0.13	0.07
Fixed O&M Recovery Required	$/kWh	0.00	0.02	0.01	0.01	0.01	0.00	0.03	0.01
Heat Rate	BTU/kWh	9200	0	0	0	9646	6752	9646	6752
Fuel Cost	$/MMBTU	1	0	0	0	1	4	1	4
(Fraction Biomass/NGCC)	%							8.8	8.2
Fuel Cost per kWh	$/kWh	0.0092	0	0	0	0.0096	0.0270	0.001	0.0022
Levelized Cost of Electricity	$/kWh	0.041	0.158	0.231	0.063	0.071	0.041	0.165	0.082
Transmission and Distribution	$/kWh	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Cost of Electricity	**$/kWh**	**0.061**	**0.178**	**0.251**	**0.083**	**0.091**	**0.061**	**0.195**	**0.112**
Cost Relative to Coal		**1.00**	**2.92**	**4.11**	**1.36**	**1.50**	**1.01**	**3.20**	**1.84**

[1] A combined wind and biomass plant (or wind and gas plant) assumes that there is 1 KW installed capacity of biomass (gas) for every 1 KW installed capacity of wind, and assumes the wind plant has a capacity factor of 35% and the biomass (gas) plant has a capacity factor of 7%, operating only as needed to eliminate the variability of the wind resource.

Cost details and the levelized cost estimates for renewable and other generation technologies are provided in **Table 2**, including in the final line the cost relative to pulverized coal generation. Overnight capital and fixed and variable operation and maintenance (O&M) costs were taken from EIA data (2009), as were heat rates. Capacity factors for the traditional plants and fuel costs were taken from a study conducted by Lazard Ltd. (Lazard, 2008). The capital recovery rate of 8.5% was calculated as the rate that gives the constant capital recovery necessary each year over the life of the plant in order to recover capital costs, taking into account discounting, and is consistent with Stauffer (2006).

For the wind with backup technologies, we assume that for every KW installed capacity of wind one KW of installed capacity of the backup (either gas or biomass) is required. Reflecting typical load curves and wind generation curves, we assume the capacity factor for the backup is 7 percent and that of the wind portion of the installation is 35 percent. Thus, about 17 percent of the electricity produced is from the backup and 83 percent is from wind. Capital, O&M and fuel costs of a wind plant are combined with those of a gas or biomass plant in the levelized cost calculation for wind with backup. The cost of transmission and distribution (T&D) for conventional sources is estimated at $0.02 per kWh (McFarland *et al.*, 2002), and we add an extra $0.01 for large scale wind with backup to account for transmission from ideal wind sites that are often some distance from load. The resulting costs relative to coal generation are shown in the final row of the Table 2.

We follow Paltsev *et al.* (2005) and model the initially limited capacity for the construction of new technologies with an initial endowment of a technology-specific fixed factor that increases as a function of installed capacity. This creates short-run adjustment costs that slow the rate of installation in early periods. The data in Table 2, along with the fixed factor, allow for the calculation of input cost shares, which are used in EPPA. The CES nest structure and input cost shares are shown in **Figure 1** for wind with gas backup and wind with biomass backup (in parentheses). The elasticity of substitution between wind and the backup technology is zero (Leontief), reflecting the requirement of complete back-up.

We implement the RPS by requiring that each unit of conventional electricity submit renewable electricity credits (RECs) in proportion to the RPS constraint as an additional input to production. RECs are produced jointly with the renewable electricity, as shown in Figure 1. If the RPS is 20%, the production of every unit of conventional electricity requires 0.2 RECs. Wind with biomass backup is considered fully renewable so each unit of generation also produces one REC. However, wind with gas backup only produces 0.83 of a REC with each unit of generation because only 83 percent of electricity is from wind and the remaining 17 percent is from gas which does not qualify as renewable. The gas is also subject to any carbon policy, and carbon permits or a carbon tax payment covering the amount of gas used must accompany production from wind with gas backup.

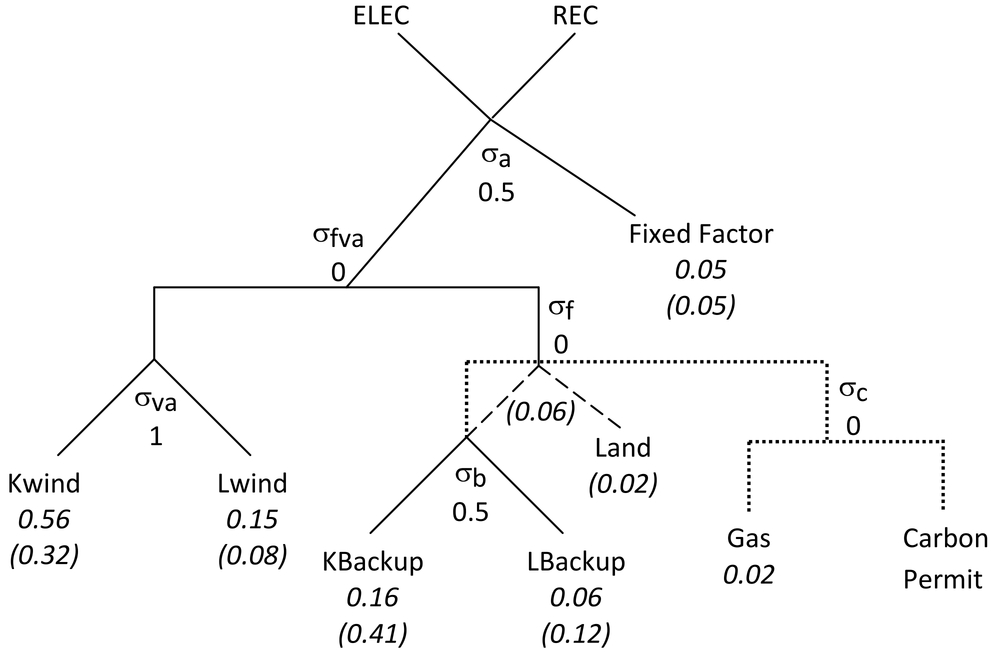

Figure 1. Production Function for Wind with Backup Technologies.

Note: Cost share parameters are shown beneath the inputs for wind with gas backup, and in parentheses for wind with biomass backup. K----. and L---- are capital and labor, respectively, for the wind generation or for the backup; σ_j are elasticities of substitution, j indicating the different nests; electricity (ELEC) and renewable electricity credits (REC) are joint outputs. The dashed-line nest with land as an input applies only to biomass backup. The dotted-line nest, with gas and carbon permit, applies only to gas backup.

3. ECONOMICS OF RENEWABLE PORTFOLIO STANDARDS

To explore the economics of renewable portfolio standards we focus on policies in the U.S. In particular, this work focuses on a cap-and-trade policy of 80% below 1990 levels by 2050.[3] This core case is labeled as 167 bmt, which is the cumulative number of allowances made available between 2012 and 2050 in billions of metric tons (bmt), or gigatons, of carbon dioxide equivalent (CO_2-e) emissions.[4]

Throughout this analysis the cap covers the emissions of the six categories of greenhouse gases identified in U.S. policy statements and in the Kyoto Protocol (CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs), with the gases aggregated at the 100-year Global Warming Potential (GWP) rates used in US EPA (2006). All prices are thus CO_2-equivalent prices (noted CO_2-e), and are in 2005 dollars. Banking and borrowing are allowed, the cap applies to all sectors of the economy except

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[3] This level of reduction is generally relevant given recent Congressional efforts to introduce a cap and trade policy. For analysis of the cost of the Waxman-Markey bill (H.R. 2454) see Appendix C to Paltsev *et al.* (2009).

[4] A complete set of results for this scenario and two other core scenarios and for variation in system features over such dimensions as coverage, banking and borrowing, trade restrictions, revenue recycling, and agricultural markets is provided in Paltsev *et al.* (2008). Paltsev *et al.* (2009) also provides analysis focusing on the 167 bmt case.

emissions from land use, and no credits for CO_2 sequestration by forests or soils are included. The policy scenarios provide no possibility for crediting reductions achieved in systems outside of the U.S., such as the Kyoto-sanctioned Clean Development Mechanism (CDM) or other trading systems such as the EU Emission Trading Scheme (ETS).[5]

3.1 Impact of RPS Policy

3.1.1 General RPS

Next we utilize the new RPS constraint to test the impact of RPS policies. We simulated general RPS policies that require either 5, 10, 15 or 20% renewables each year from 2015 to 2050. In this set of scenarios, a 20% RPS would start in 2015 requiring 20% renewables and would have that same requirement until 2050. There are only slight variations in the emissions paths for the various levels of RPS added to the 167 bmt cap-and-trade, which are due to differences in banking as it interacts with the RPS. All cases show net banking, with GHG emissions below allowances in early years and exceeding allowances in later ones. By design, all cases meet the 167 bmt cumulative cap for the period 2012 to 2050.

Figure 2 shows the effect of adding the various levels of RPS requirements to the 167 bmt cap-and-trade policy on welfare change and CO_2-e price in 2030. In the figure 0% RPS is the 167 bmt cap only. As the level of RPS added to the cap-and-trade policy increases, the welfare loss increases. Comparing the no RPS case to the 20% RPS, welfare loss increases from less than 1% to nearly 1.7%, representing about a 70% increase in cost. Beyond 2030, the difference in welfare change due to the RPS level decreases because there has been significant time to adjust to the policy and make investments in renewable technologies that bring down costs in the later years. As the figure shows, an RPS combined with a cap-and-trade policy achieves the same emissions as a cap-and-trade only policy but at a greater cost.

Alternatively, as the level of RPS added to the cap increases, the CO_2-e price decreases. The price is 107/tCO_2-e under the cap-and-trade alone and \$85/tCO_2-e under the cap with a 20% RPS. This represents a 21% decrease in price. While the CO_2-e price can be a general indicator of the strength and cost of a greenhouse gas mitigation policy, if that policy combines cap-and-trade with other policies then the CO_2-e price can be a misleading indicator of the amount of emissions controlled and the total cost of the policy. In this case, for a fixed GHG reduction CO_2-e prices are lower the larger the RPS. On the other hand, the total cost to the economy, measured as change in welfare, is larger the larger the RPS, with no gain in emissions reductions.

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[5] Because there can be trade effects from policies abroad, we specify climate policies in other regions. We follow the convention of the Energy Modeling Forum (EMF) (Clarke *et al.*, 2009) and specify the following policies: developed countries reduce to 50% below 1990 levels by 2050; China, India, Russia, and Brazil start in 2030 on a linear path to 50% below their 2030 emissions level by 2070; and the rest of the countries delay action beyond the 2050 horizon of our study. There is no emissions trading among regions.

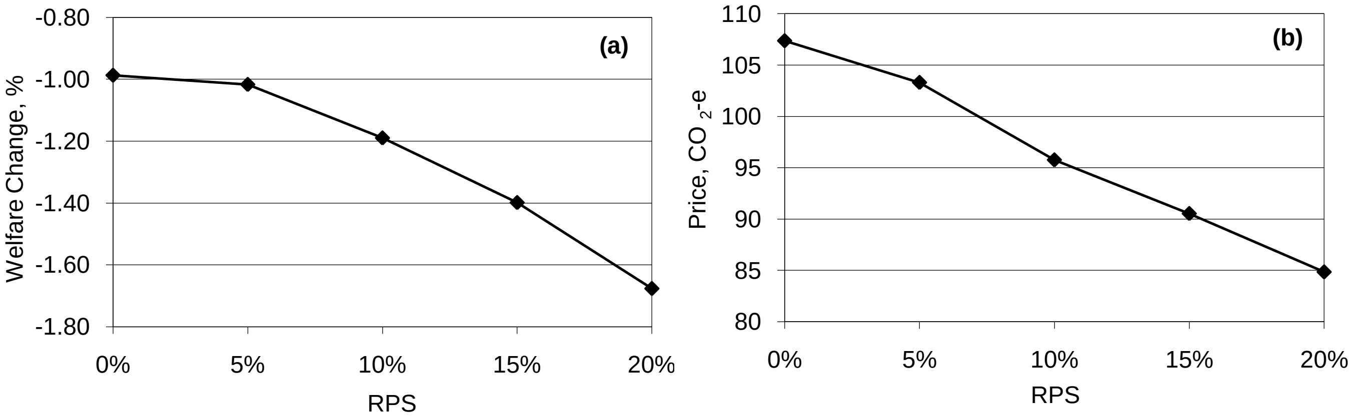

Figure 2. Impact of Various Levels of RPS Targets Added to a 167 bmt Cap-and-Trade Policy: **(a)** Welfare Change in 2030 and **(b)** CO_2-e Price in 2030.

We illustrate the effect of the RPS on CO_2-e prices using a hypothetical marginal abatement cost (MAC) curve. In **Figure 3a** the MAC without RPS represents a cap-and-trade only policy: a target (the cap) is set for a specific amount of emissions reductions. The resulting CO_2-e price (P_{Cap}) is where the cap meets the MAC curve. The MAC with RPS represents a cap-and-trade policy with the addition of a binding RPS. The additional renewables required beyond that which the cap-and-trade would bring forth creates a horizontal shift of the MAC curve to the right, by the amount of carbon reduced by the additional renewables. The shifted curve now results in a lower CO_2-e price ($P_{Cap+RPS}$).

Turning to the full cost of the RPS, **Figure 3b** demonstrates the general impact of the RPS on the electricity market under marginal cost pricing of electricity, and assuming a constant returns to scale conventional generation technology. Mandating more renewables increases the price of electricity, reducing the total quantity of electricity demanded and the amount of fossil electricity. Area A+B+C+D represents the loss in consumer surplus because of the higher electricity price. Area A is the gain to renewable producers due to the RPS. Area C is the gain to remaining fossil producers who receive the higher electricity price. This leaves area B+D as deadweight loss from the RPS policy—area B is loss from inefficient production (forcing more expensive renewables instead of cheaper fossil production) and area D is loss from lower consumption due to the higher price.

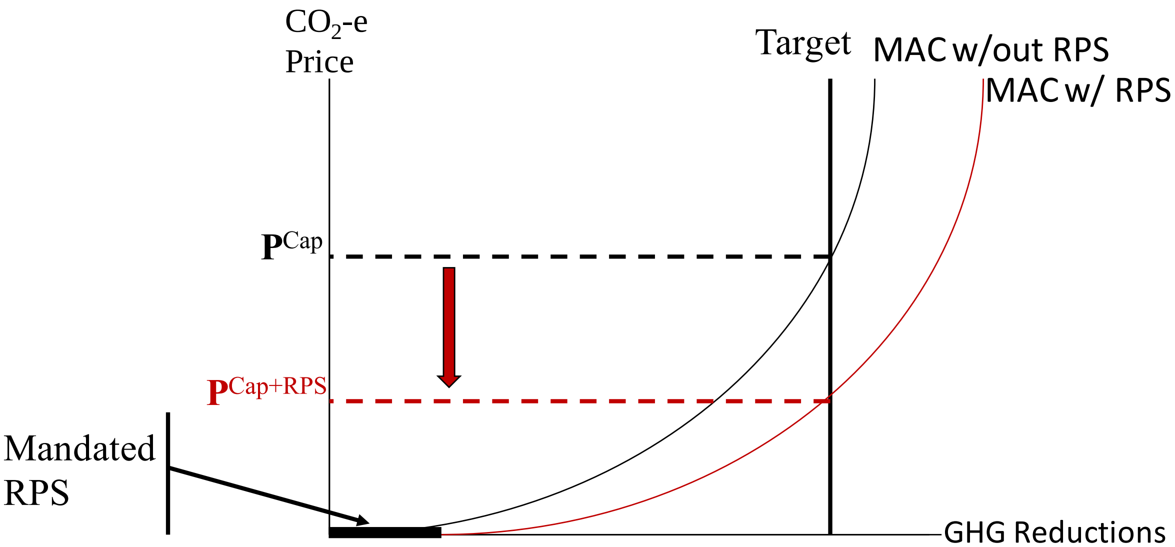

Figure 3a. MAC Curves with and without an RPS.

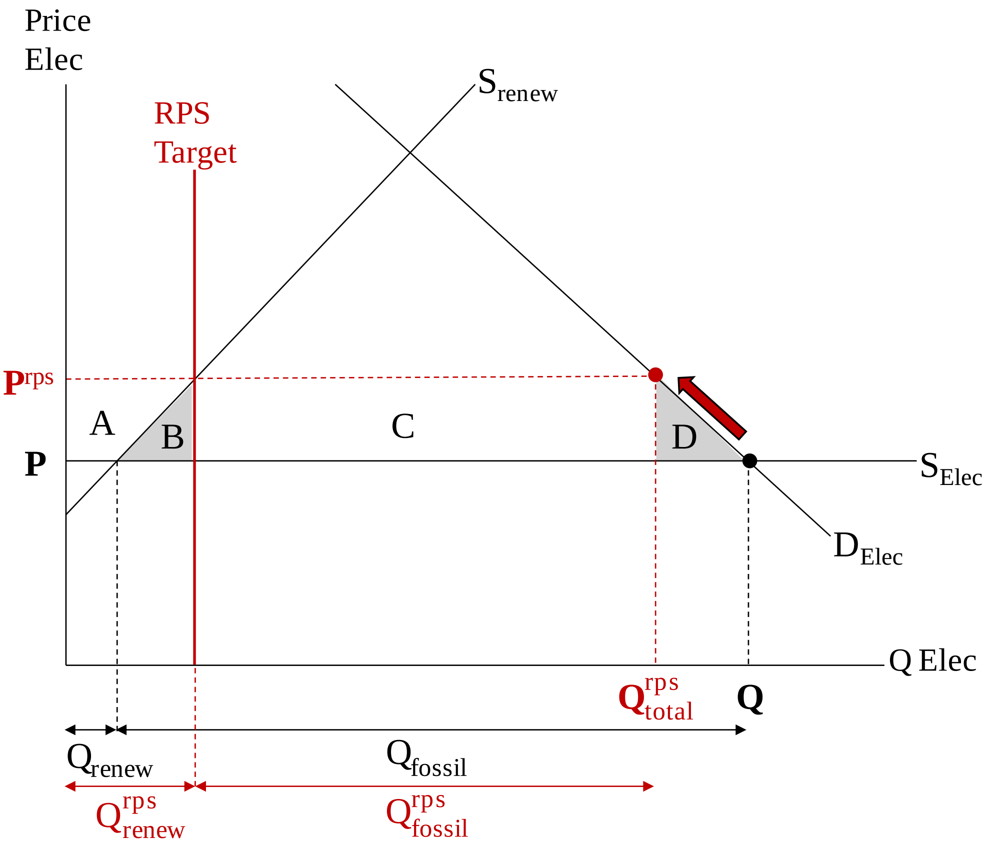

Figure 3b. Impacts of an RPS Policy with Marginal Cost Pricing of Electricity. A: gain to producers of renewable electricity, B: deadweight loss, C: gain to producers of fossil-based electricity, D: deadweight loss, A+B+C+D: reduction in consumer surplus.

As noted, the illustrated case is for marginal cost pricing. Markets for electricity distribution are regulated and so consumers would not see a rate that reflected the marginal cost of renewables but rather a cost that averaged in the marginal cost of renewables, reflected in a RECs market. Using terms from Figure 3b, a representation of this pricing structure is:

$$\mathrm{P}^{\mathrm{AC}} = \frac{\mathrm{P}^{\mathrm{rps}} * \Delta \mathrm{Q}_{\mathrm{renew}} + \mathrm{P} * \mathrm{Q}_{\mathrm{fossil}}^{\mathrm{rps}}}{\mathrm{Q}_{\mathrm{total}}^{\mathrm{rps}}}$$

Where P^{AC} is the average cost price of electricity, $\mathrm{P}^{\mathrm{rps}}$ is the marginal cost of renewable electricity and P is the (constant) marginal cost of fossil electricity. Only the change in $\mathrm{Q}_{\mathrm{renew}}$ matters as the original amount of renewables is already rolled into the marginal cost in the market outcome. Consider an example where at the market price (P) renewables make up 5% of total electricity. An RPS target of 15% increases the share of renewables by 10%. If at $\mathrm{Q}_{\mathrm{renew}}^{\mathrm{rps}}$ renewables are 40% more expensive than fossil electricity, the electricity price would increase by 4% (.10*.40) under average cost pricing, instead of the full 40% in full marginal cost pricing. In relation to Figure 3b, this is a smaller price increase so area D loss would be smaller due to less reduced demand, area C would be much less implying less transfer from consumers to producers, and area B loss would be the same size. The EPPA model assumes marginal cost pricing which tends to have a greater price response but also a greater carbon response due to a larger decrease in fossil electricity demand.

3.1.2 Phased in RPS

To provide further insight into policy options more similar to those being considered in the U.S., we consider an RPS that is phased in. We represent an RPS with targets of 9.5% in 2015 and 20% in 2020 to 2050. To help put these RPS targets into context, it is helpful to look at the penetration of renewables under business as usual assumptions. Today in the U.S., renewables are responsible for roughly 3% of electricity production, according to EIA data. The model used in this analysis predicts the non-hydroelectric renewable share under business as usual to be around 3%, falling somewhat in later years as other generation sources expand more rapidly to meet growing demand. This result is similar to other studies. For example, Palmer and Burtraw (2005), using the Haiku electricity market model, have a baseline forecast of generation by non-hydro renewables of 3.1% of total generation by 2020.

Figure 4 shows the GHG emissions paths for the 167 bmt cap-and-trade only policy, the RPS alone according to the targets described above, and the combination of the cap and RPS. The RPS alone does not significantly reduce emissions, and results in 308 bmt cumulative emissions over the course of the policy. The cap alone and the cap with the RPS both result in 167 bmt cumulative emissions.

Combining the RPS with the cap results in higher welfare costs than the cap alone (see **Figure 5**). Even though the RPS is phased in, it is more binding in early years, with substantially higher welfare costs through about 2035. In later years the RPS is no longer binding and welfare changes are similar for the cap alone and the cap with RPS. This happens because the rapid increase in the requirement creates additional short term adjustment costs that disappear as this capacity expansion constraint becomes less binding. However, because of the larger welfare losses in early years, the net present value (NPV) of welfare cost of this combined RPS and cap policy is worse than a cap alone. The NPV of welfare change over the policy period is -1.16% for the cap alone and -1.44% for the cap with the RPS. This represents a 25% cost increase as a result of adding the RPS to the cap-and-trade. This means that adding an RPS to a cap achieves the same amount of emissions reductions but at significantly greater costs. The RPS alone has a NPV of welfare change of -0.71%, which is costly considering how few emissions reductions it achieves.

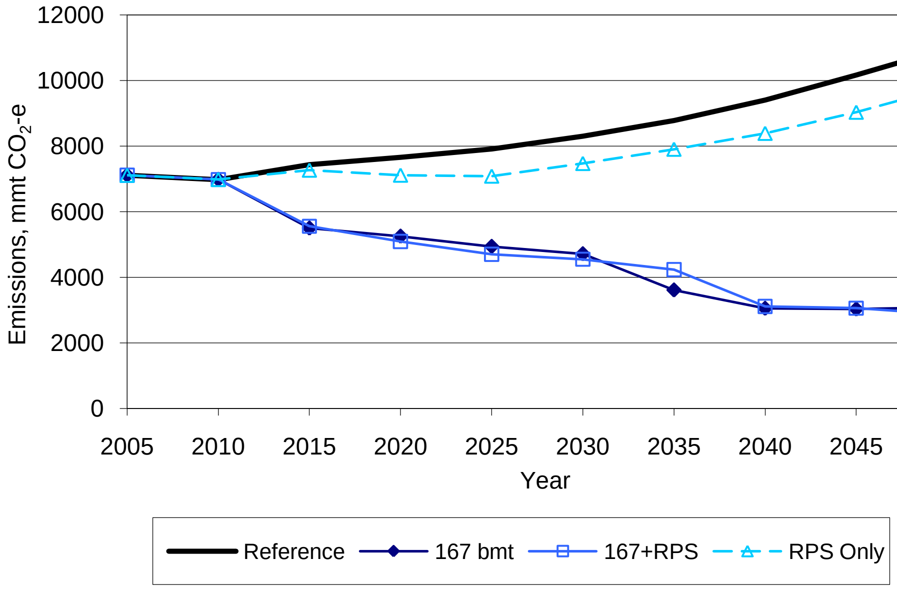

Figure 4. GHG Emissions Paths.

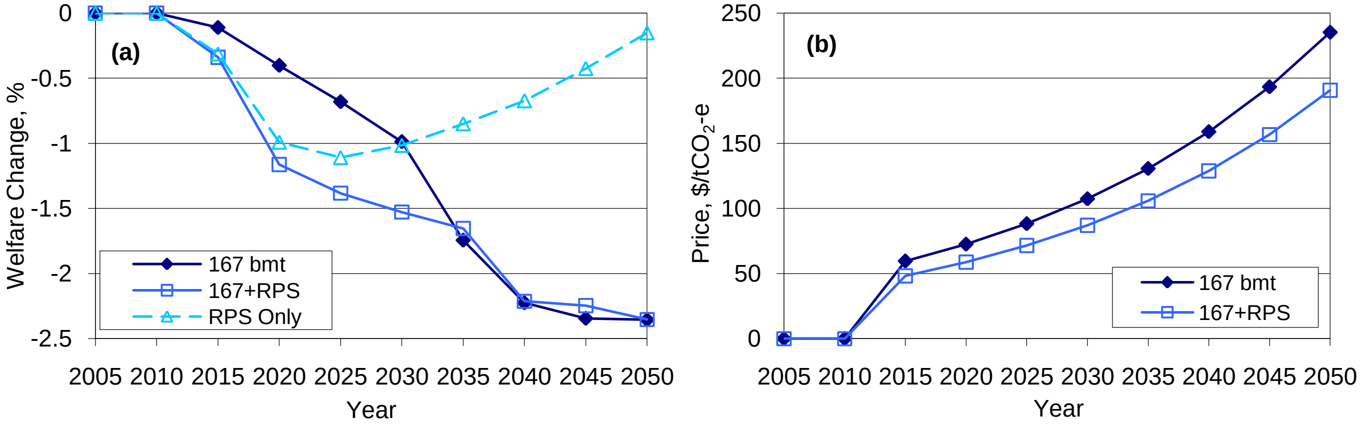

Figure 5. Impact of Different Policies: **(a)** Welfare Change and **(b)** CO_2-e Price.

Although adding the RPS to the cap increases the welfare cost, it decreases the CO_2-e price (see Figure 5). With the cap alone the price starts at about $60 per ton CO_2-e in 2015 and rises to $235 per ton CO_2-e in 2050. When the RPS is added to the cap the initial 2015 price is reduced to $48 per ton CO_2-e and rises to about $191 per ton CO_2-e in 2050, a reduction of about 19%.

Figure 6 compares the electricity generation by source of the reference, cap only, cap plus RPS, and RPS only cases. Wind with backup and other renewables together achieve the RPS target. Adding the RPS to the cap reduces generation by coal and natural gas. The RPS requires that these cheaper generation sources be replaced by more expensive renewables. In the cap alone, renewables are only about 3% of generation in all years. Natural gas combined cycle (NGCC) and reducing electricity use are determined to be the most cost-effective strategies for reducing emissions. In the cases with an RPS, other renewables ramp up in early years to meet the renewables target. However, as the target becomes more stringent wind with backup (particularly gas backup) becomes more cost-effective than the other renewables. This occurs because there is an increasing penalty on other renewables as they increase as a percentage of total generation (because of assumptions about intermittency discussed in Section 2.2). In the case of the RPS only policy, coal use is still significant as the policy is not stringent enough to further reduce coal generation.

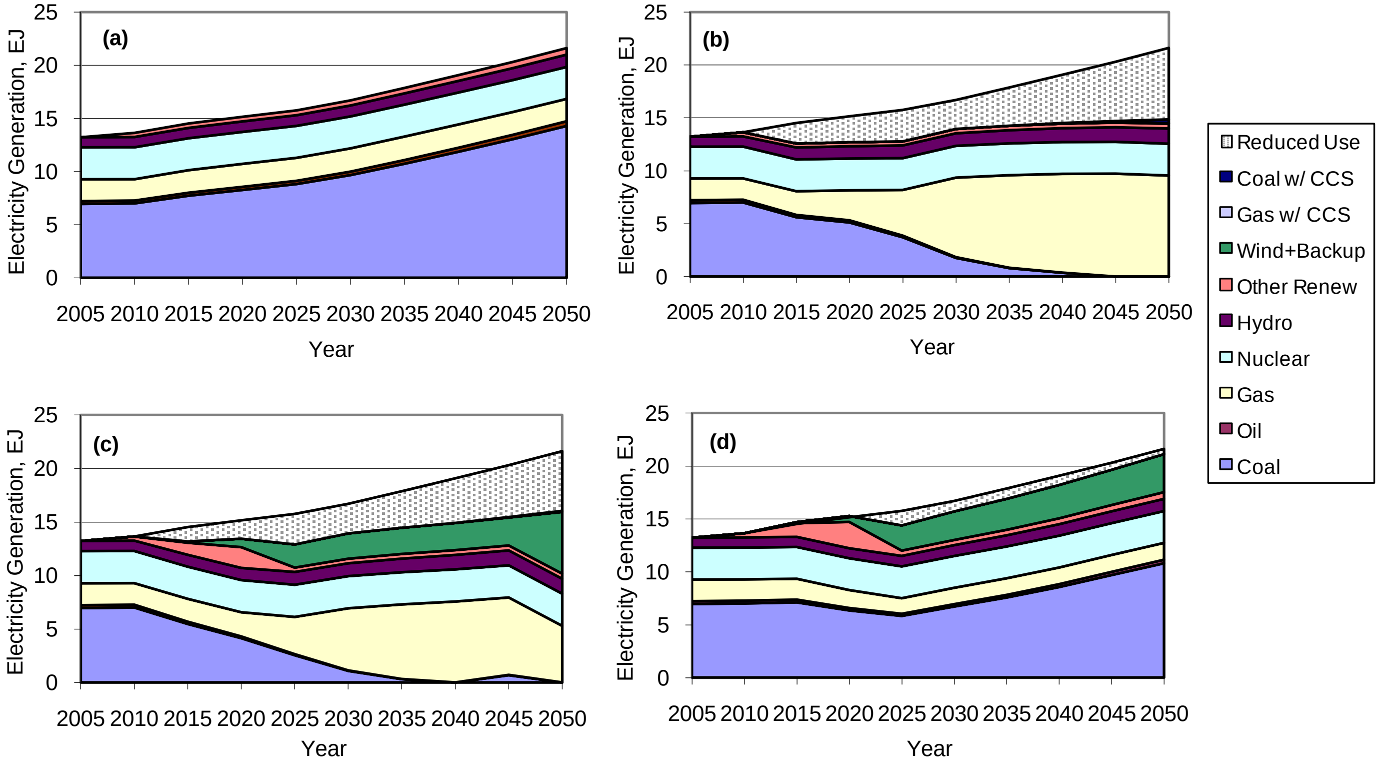

Figure 6. Electricity Generation by Source: **(a)** Reference **(b)** 167 bmt, **(c)** 167 bmt with RPS, and **(d)** RPS Only.

For the cap with RPS, renewables actually expand beyond the 20% required by the RPS, rising to almost 40% of total electricity in 2050. This happens because in earlier years the RPS required the development of wind with backup. This increased the level of fixed factor in later years, lowering the adjustment costs at a time when renewables are becoming more economic relative to fossil technologies due to the increasing CO_2-e price. Thus by the later years of the policy it is more cost-effective to continue to expand renewables with backup than to start to develop CCS, expand NGCC, or further reduce use.

3.2 Sensitivity

To test the sensitivity of the results above to the technology and cost assumptions made, we created three additional scenarios with different assumptions. In the first scenario case, the cost of CCS technologies is decreased (case denoted “low ccs cost”). For coal with CCS and gas with CCS the cost relative to conventional coal generation is decreased from 1.6 and 1.6 to 1.19 and 1.17, respectively. In the past CCS was thought to be less expensive than current assessments and it is possible that developments take place that reduce cost estimates once again. In the second and third cases, the cost of all renewable technologies are increased by 25% (cases denoted “high renew cost”) and decreased by 25% (case denoted “low renew cost”). These cases explore the situations in which renewables cost more or less than expected.

For the cap with RPS policy, coal with CCS dominates after 2030 when CCS costs are low. With high renewable costs, the electricity mix is very similar to that of the base cap plus RPS case, except renewables do not expand beyond the required target in 2050 because they are so expensive. With low renewable costs, renewables are very cost effective and expand well beyond their RPS requirement starting in 2035. In 2035 renewables are 45% of total electricity and increase to 72% by 2050. This case implies the importance of bringing down the cost of large scale renewable technologies.

Figure 7 compares the welfare changes in the base case and sensitivity cases for the cap with RPS policy. The low CCS cost results in lower welfare costs. Because the RPS forces a significant percentage of renewables, the high renewable cost case significantly increases the welfare cost. Alternatively, the low renewable cost significantly decreases the welfare cost. For the RPS only, the same pattern emerges except the low CCS cost does not make a difference because an RPS alone policy does not bring in CCS. Of course, the cost of renewables drastically affects the cost of meeting a policy involving an RPS. In the case of a cap alone, the low CCS cost reduces welfare cost even more relative to the base case. The high renewable cost does not affect the welfare compared to the base case because the cap alone uses only small quantities of renewables. The low renewable cost brings large amounts of renewables into the cap only case and reduces welfare costs slightly compared to the base.

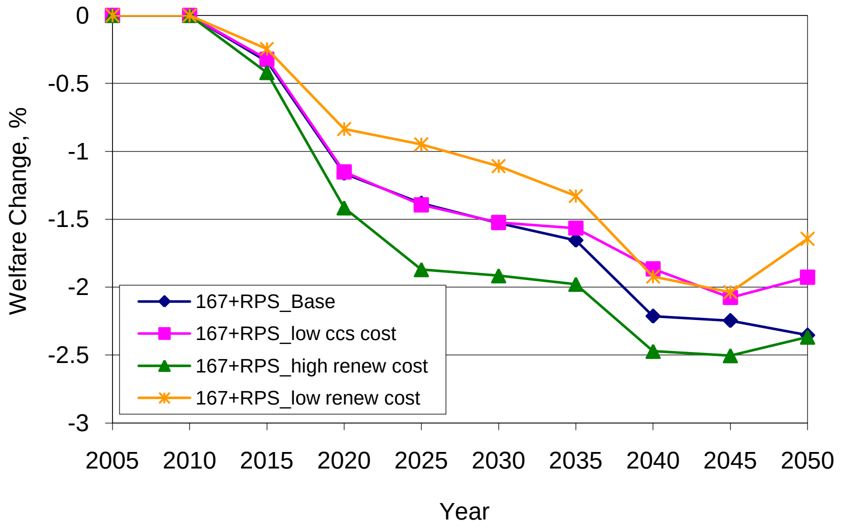

Figure 7. Welfare Change for 167 bmt with RPS.

In terms of NPV welfare costs over the whole period, when an RPS is added to a cap the cost of the policy significantly increases. The NPV cost of the policy increases by 25% in the base case, 39% in the low CCS cost case, 48% in the high renewable cost case, and 4% in the low renewable cost case. These large increases in costs are a result of the RPS policy preventing the use of least-cost options and instead forcing the use of renewables, regardless of their cost. Without the RPS, the cap alone has the flexibility to meet the 167 bmt target with the most cost-effective technologies. Adding the RPS to the cap removes this flexibility, which proves immensely costly when renewables turn out to be more expensive than expected. This point highlights a key problem with an RPS: it picks technology winners that may not prove to be the best or cheapest. A cap alone does not pick winners, but provides incentives to develop the technologies that can meet the cap in the most cost-effective way. NGCC and reduced use are the most cost-effective way in the base case. If CCS is cheaper, that is more cost-effective. If renewables are less expensive, or perhaps if NGCC turns out to be more expensive, then renewables would enter as a cost-effective way to meet the cap.

Different technology cost assumptions also impact the CO_2-e prices (see **Figure 8**). Compared to the base case, low renewable costs reduce the CO_2-e price for both the cap alone and cap with RPS policies. In this case, the addition of the RPS to the cap reduces the price by about 16% in each year. Low CCS costs reduce the CO_2-e price even more below the base case for both the cap and cap with RPS policies. However, the difference between the policies is less, with the addition of the RPS to the cap reducing the price by about 12%. High renewable costs result in almost the same CO_2-e prices as the base case for both the cap alone and cap with RPS, and therefore are not shown in the figure. For the high renewable cost assumption there is almost no impact on the CO_2-e price for the cap alone because there is very little renewable generation. However, for the cap with RPS policy the fact that the high renewable cost case results in nearly identical prices as the base case means that the RPS is doing an excellent job of hiding the cost of the policy. Even though the welfare costs are much higher with the high renewable costs, the CO_2-e price is almost the same.

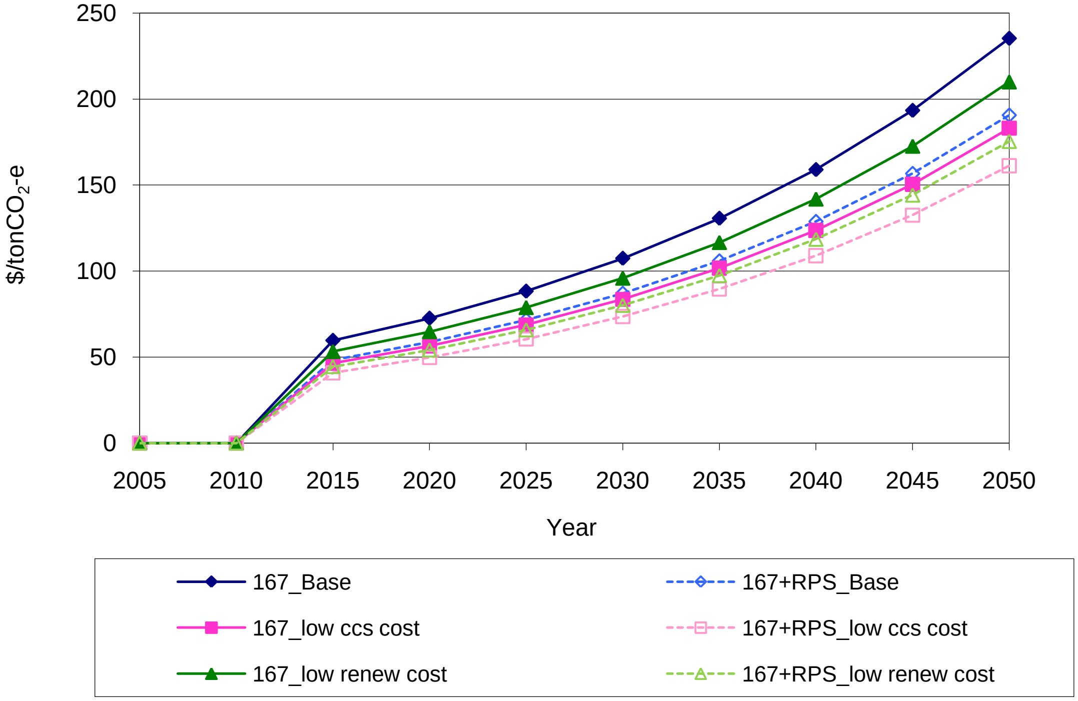

Figure 8. CO_2-e Prices.

4. CONCLUSIONS

We investigated the effects of climate policy options using a computable equilibrium model of the economy, the EPPA model. Renewables are generally not well represented in macroeconomic models, which often do not capture the variability of the resource. Here, we augmented the EPPA model to better represent renewable energy. In particular, we developed an approach representing the possibility of integrating small amounts of wind into the grid at increasing costs while also representing the need to match supply with load at larger scales of the variable renewable. There are a variety of options to balance this supply and demand, including storage, load-shifting and backup capacity of dispatchable generation technologies. We represent the latter.

We also developed a system that allows REC trading to model an RPS. We then used the revised model to investigate the role and cost of an RPS requirement as part of a broader GHG reduction policy. We simulated three policy options: a cap-and-trade alone that reaches 80% below 1990 levels by 2050, an RPS alone at various levels, and the cap combined with the RPS.

Our study shows that as you increase the RPS requirement from 5 to 20%, in combination with a cap-and-trade policy, the emission level remains unchanged, the CO_2-e price falls, and the full measure of the cost of the combined policies—the welfare cost—rises substantially. Adding the 20% RPS to the cap-and-trade policy increases the NPV welfare cost by 25 percent over the life of the policy. At the same time, the addition of the RPS reduces the CO_2-e price by about 20 percent each year, thereby hiding the additional welfare costs.

When phasing in the RPS, it is more binding in early years, but no longer binding in later years. There is a benefit of the RPS because capacity expansion in early years increases the level of fixed factor in later years when renewables become economic. As a result renewables face lower adjustment costs in later years. However, because of the large welfare losses in early years, the NPV of welfare cost of this combined RPS and cap policy is still worse than a cap alone.

Using different technology and cost assumptions increase or decrease the cost of the policies. When renewables are 25% more expensive, adding an RPS to a cap increases the cost of the policy over the whole period by 48%. This highlights a key issue with an RPS: it picks technology winners regardless of their cost-effectiveness. An RPS shifts investment away from the least-cost emission reduction options and toward these specific renewable technologies, which are not necessarily least-cost or even low-cost. Thus, by removing the flexibility to pursue the least costly emission reduction strategy, an RPS adds to the economy-wide cost of the policy.

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