Representing technology in CGE models: a comparison of SGM and AMIGA for electricity sector CO_2 mitigation

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Abstract: The goal of this effort is to compare two climate economic models – the Second Generation Model (SGM) and All Modular Industry Growth Assessment Model (AMIGA) – and highlight the consequences of different modelling approaches and structures on the estimation of climate change policy results. We show that different assumptions about how technology choices are made in the US electricity sector in response to a carbon charge can lead to differences in estimates of environmental, fuel market, and economy-wide impacts. If the differences among models can be better understood, improvements in the models may be made and policy makers will be better informed by the insights provided by the models.

Keywords: climate economics modelling; electricity sector technologies; renewable energy; energy sector investment.

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1 Introduction

Over the last decade, extensive economic analysis of climate change policies has been conducted both in the USA and around the globe. The current standard for conducting economy-wide analysis is the use of Computable General Equilibrium (CGE) models, which attempt to capture the response of the whole economy to a climate policy.

Unfortunately, the complexity of the general equilibrium structure is hard to understand even for the most informed observer. The models have a 'black box' quality to them which makes it difficult to assess their key underlying structure and empirical parameters that determine model outcomes. For those who use these models, it has been difficult to disentangle detailed input assumptions from the structural aspects of the models in assessing their capabilities.

In this paper, we present results and insights from a model comparison exercise involving two CGE models – the Second Generation Model (SGM) (Edmonds et al., 2004; Fawcett and Sands, 2005; Sands and Fawcett, 2005)[1] and the All Modular Industry Growth Assessment Model (AMIGA) (Hanson and Laitner, 2004; Hanson et al., 2003, 2004).[2] Both models have been widely used to assess energy, economy, and greenhouse gas mitigation issues over the last decade. Both have multiple global regions, and incorporate a full set of greenhouse gas emissions. Both have explicit connections between technology and the economy, and vintaged capital stocks. Additionally, both are disaggregated to reflect the relative importance of various sectors in determining greenhouse gas emissions.

While the two models are similar in many ways, they are distinctly different in some aspects of their model design. What distinguishes AMIGA from many other CGE models is the unusually high level of technological detail in the energy sector – both on the demand and the supply side – and the novel way that it represents the mechanics of non-price policies (e.g., programs that provide information about conservation opportunities, appliance standards, etc.) In addition, AMIGA allows for the sub-optimal use of factors of production in the economy.

SGM, on the other hand, is a CGE model that assumes full employment of resources. While SGM generally has less technology detail than AMIGA, it does explicitly represent electricity supply-side technologies as part of its modelling framework. However, outside of the electricity sector in SGM, technology is generally modelled in its 'reduced form' (e.g., as embodied in the model's production functions).

While each model – SGM and AMIGA – has been used to produce policy analysis of greenhouse gas mitigation policies, no one has sought to directly compare and contrast in detail results from the two models and attempt to relate the differences in their results to each model's structure. Given that the two models are sufficiently elaborate, a comparison of all aspects of both models would be very difficult. Thus, we decided from the outset of this effort to undertake a highly detailed, but more modest, assessment.

In this exercise, we attempt to standardise key electricity generation sector cost and performance assumptions as well as a variety of key aggregate variables (e.g., growth in gross domestic product, growth in electricity demand, energy prices). Then we run a selected number of common policy experiments that influence carbon emissions in the US electricity sector. We chose to focus on electricity generation because of the importance of this sector in greenhouse gas emissions, and because both models have relatively rich representations so that the comparison would be expected to yield

interesting results. The richness of the representation allows for a detailed view of the evolution of technology choice through time in response to a climate policy.

To address this topic, first we report on one policy experiment: a $50 carbon charge in the US electricity sector implemented from 2010 to 2015 that rises to $100 thereafter. To facilitate the model comparison, we also analyse a set of 'constant' carbon price experiments that allow for the construction of Marginal Abatement Cost (MAC) curves for the US electricity sector for each model.[3] We report our results through the year 2025. All dollar figures reported are presented in year 2000 US dollars.

This rigorous comparison of model structure is unusual in the field, and is a first step before understanding how these models treat a variety of other types of carbon abatement policies. While each model represents emissions and technologies for non-CO_2 gases, our focus on the electricity sector allows us to ignore these emissions for purposes of this comparison.

In the next section of the paper, we examine and compare the key structural equations in each model that influence technological choices, substitution possibilities, and the response of the electricity sector to a climate policy. We also look at how these responses in the electricity sector are transmitted throughout the whole economy. Next we briefly review the standardised 'Base Case' used for model comparison. We then turn to a discussion of key results from this exercise. Last, we discuss what we learned and draw conclusions.

2 Electricity sector representations

2.1 SGM

The SGM electricity sector is designed to assess how greenhouse gas policies, principally a carbon price, will affect the choice of technology in this sector (e.g., Pulverized Coal (PC) vs. Natural Gas Combined Cycle (NGCC) plants) and possibly lead to the early retirement of existing capital stocks at a nationally aggregated level. In response to a carbon price, SGM seeks to evaluate the mix of electricity generating technologies that achieves a carbon abatement goal at least cost, while allowing for the lifetimes and efficiencies of different types of power plants to be maintained at reasonable levels. In turn, the cost of a policy option can be analysed.

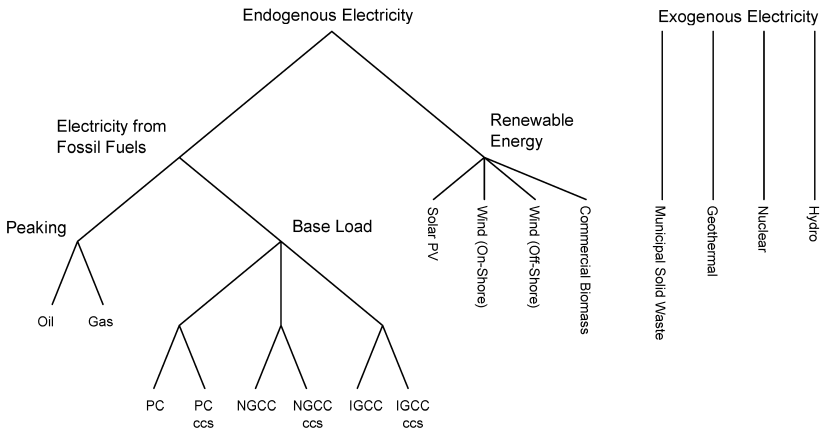
Within each of SGM's five-year time steps, investment for new electricity generating capacity occurs at both the sector and technology level. A production sector in SGM is defined for each unique product; in this case, electricity. Technologies within the electricity sector represent various ways of producing electricity. Investment is allocated to some electricity technologies exogenously, such as nuclear and hydro, but for other technologies is allocated using a nested logit function (Clarke and Edmonds, 1993; Sands, 2004).[4] The full set of technology options and the nesting structure used in the SGM electricity sector is shown in Figure 1.

At each nest in Figure 1, investment shares are calculated using equation (1):

$$\text{share}_j = \frac{b_j C_j^{\lambda}}{\sum_k b_k C_k^{\lambda}} \tag{1}$$

where j is an index over technologies or subsectors within a particular sector; $share_j$ is the investment share for the technology j; C_j is the levelised cost per kilowatt-hour (kWh) for an individual technology; b_j is a calibration parameter for the jth technology; k represents an alternate index over the total number of technologies within a particular sector; and λ determines that rate that one technology can substitute for another.

Figure 1 Electricity generating technologies: oil-fired (Oil), natural gas single cycle (Gas), Pulverized Coal (PC), PC with carbon dioxide capture and storage (PC ccs), coal Integrated Gasification Combined Cycle (IGCC), coal IGCC with carbon dioxide capture and storage (IGCC ccs), Natural Gas Combined Cycle (NGCC), NGCC with carbon dioxide capture and storage (NGCC ccs), solar PV, on-shore wind, off-shore wind, commercial biomass, municipal solid waste, geothermal, hydropower, and nuclear



The λ parameters vary at each level of the nest, and they must be negative so that an increase in levelised cost implies a decrease in investment share. This allows lower cost technologies to be favoured, yet prevents 'knife edge' switching between technologies. For the share between the advanced fossil technologies (i.e., Natural Gas Combined Cycle (NGCC) and coal Integrated Gasification Combined Cycle (IGCC)) and the equivalent technologies with carbon dioxide capture and storage, λ is set at a high absolute value to ensure that the more expensive carbon dioxide capture and storage technologies are only chosen in the presence of a carbon policy that makes them economically competitive.

In order to match observed and projected electricity generation shares in the model base year, SGM utilises the b_j parameters to favour some technologies over others. These b_j parameters, which remain constant over time in SGM, help to implicitly represent some of the ways technologies compete that are not captured by engineering cost data.

For example, since IGCC plants are a new technology, there may be some risk associated with adopting them, and fewer plants might be built than implied by the levelised cost alone. Further, some renewable energy technologies may produce power intermittently, or incur increased transmission and distribution costs, that are not explicitly captured in SGM. Thus, the b_j parameters are required for the logit sharing mechanism to implicitly capture these market characteristics and select the appropriate level of investment.

One of the central challenges with this approach is the treatment of relatively new technologies such as IGCC. As IGCC plants penetrate the market, the risk associated with their adoption may decrease making the technology more economically attractive. This increase in attractiveness could be implemented in SGM by allowing technical coefficients of the IGCC production function to change over time. For example, the energy conversion efficiency of the production process could increase over time or capital costs could decrease over time. Either change reduces the levelised cost per kWh of electricity generated from IGCC technologies, resulting in a greater share of new investment.

Levelised cost per kWh of the jth technology, C_j, is calculated in SGM as a transformation of the unit cost function as in equation (2):

$$C_j = \frac{\frac{1}{\alpha_{0,j}}\left[\sum_{i=1}^{M}(p_i/\alpha_{i,j})^{1-\sigma}\right]^{\frac{1}{1-\sigma}}}{elecfac} \tag{2}$$

where j is an index over subsectors or technologies; i is an index over inputs; M is the number of inputs, including labour and capital; α_{0j} and $\alpha_{i,j}$ are parameters of the Constant Elasticity of Substitution (CES) production function for the jth technology; p_i is the price of input i; and σ is the elasticity of substitution, which is fairly low for the specific technologies modelled in the electricity sector. The numerator of this expression is the unit cost function,[5] measured in millions of dollars per unit of output; and the denominator, *elecfac*, is the conversion factor from units of output in dollars to units of output in terawatt hours (TWh), and is measured in TWh per unit of output. The result is levelised cost, C_j, measured in mills per kWh.

This formulation of electricity investment in SGM enables the different electricity generating technologies to compete with each other based on cost, and through the logit sharing mechanism, still allows for multiple technologies with different costs to co-exist. Furthermore, the use of the b_j parameters helps the model capture some aspects of the investment decision in electricity that are not solely based on levelised cost.

2.2 AMIGA

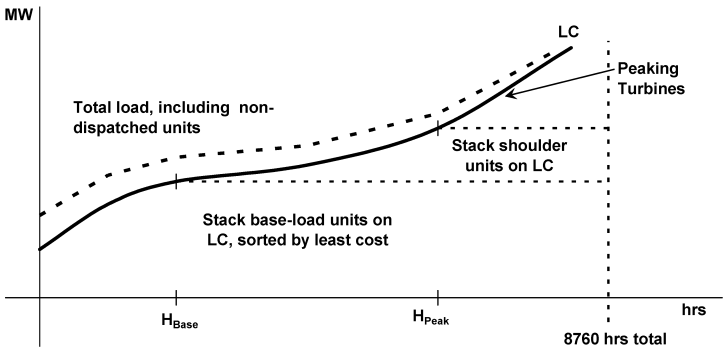
AMIGA's electricity sector model is designed to examine how electricity is provided at least cost while simultaneously meeting a carbon constraint. The model can examine the evolution of different types of power plants through time and looks at how new technologies can penetrate the electricity market in response to a carbon constraint. While AMIGA has significant technology detail on both the demand and supply-side of the electricity sector, we focus on its supply-side to facilitate comparison with SGM.

The process by which electricity production is allocated across electric generating technologies is quite a bit different in AMIGA compared with SGM. Figure 2 illustrates how the annual Load Curve (LC) facing mature, dispatchable generating technologies is constructed and how the generating units are ordered on the LC for AMIGA. The LC shows expected power demand and generation for each hour of a given year.

To obtain the LC, it is necessary to subtract non-dispatchable generation from total load. Non-dispatchable sources include intermittent renewable generators, cogenerators, and small distributed generators. This result yields net generation by hour facing centrally dispatched power plants: coal, nuclear, NGCC, and peaking turbines. The below figure

labels the switch point at which the last coal unit is loaded, H_{Base}, and the first peaker turbine is loaded, H_{Peak}. These switch points effectively divide the LC into three segments: base, shoulder, and peak.

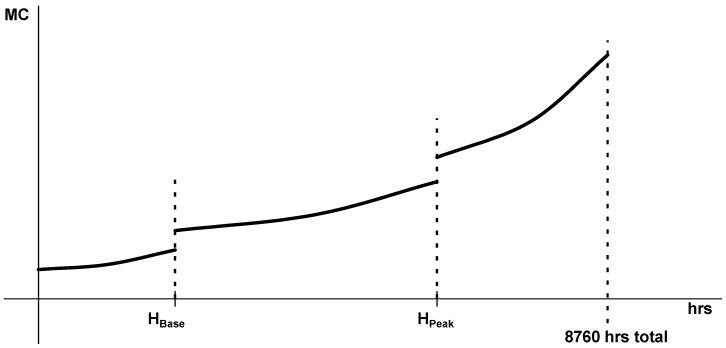
Figure 2 AMIGA Load Curve (LC) diagram



Available generating units are 'stacked' to compose the LC in the order of least variable cost as shown in Figure 2. Normally, nuclear units have the lowest variable cost, then newer coal units, then older existing coal units, then NGCC, then old gas and residual oil boiler units (where they still exist), and finally gas and distillate oil peaking turbines.

The variable cost, i.e., marginal cost, for these units can be plotted as a function of the point on the hour axis of the LC at which a unit just becomes economic to run. This marginal cost function is illustrated in Figure 3. Marginal cost will be an increasing function along the hour axis because units are dispatched in order of marginal cost. Within a plant category (e.g., existing coal units), the graph showing marginal costs may appear to be almost continuous, since marginal cost may increase only slightly from one unit to the next in the loading order.

Figure 3 AMIGA marginal cost diagram



However, there are substantial discrete jumps in marginal cost at the switch points, at which all of one type of generating unit has been loaded and the next lowest marginal cost unit is a new generating category (e.g., the marginal cost of running an NGCC unit will be much greater than that of a coal unit). It is the dispatchable units, mostly fossil fuel units, that are on the margin and, hence, they determine marginal costs.

Because existing power plant units have variation in their heat rates (i.e., a power plant's efficiency varies inversely with its heat rate), changes in fuel prices and/or emission charges can change the marginal cost of running a unit and impact the loading order of generating units. For example, a carbon charge will tend to increase the capacity factor of more efficient units and decrease the capacity factor of less efficient units.

Key questions are how much base load capacity should be built and how much peaking capacity should be available. The economic criteria for building a power plant are much like the conditions for market entry. Firms have an incentive to enter a market as long as there are rents to be earned, where average price is greater than Long-Run Marginal Costs (LRMC). For a power plant, the LRMC for increasing output by 1 kWh is the full levelised cost. Hence, the present value of total revenues must cover full present value costs in order to provide an incentive for new investment.

The very low carbon technologies such as wind, photovoltaic, solar thermal power, geothermal, biomass, and even new nuclear designs and IGCC, are developing, not yet mature, technologies. Of these technologies, the renewable technologies are represented in the electricity sector model as gradually gaining market share, x_t, from an initial small market share according to the logistic function that has been used widely in the economic literature on technology adoption. The logistic function can be expressed in a recursive, dynamic form:

$$x_{t+1} = x_t \times (1 + b \times (y(p) - x_t)) \tag{2}$$

where y is a forecast of the eventual market share and b is related to the growth rate occurring at low market shares. Since these developing renewable technologies sell available output at the price of electricity, p, the eventual market share is endogenously determined within the model by the ratio of p to the levelised cost of the renewable technology.

AMIGA takes nuclear power and the share of new coal capacity that is IGCC to be exogenous. IGCC is more expensive than a new state-of-the-art PC unit, so if IGCC captures some market share, it does so for reasons other than cost. For example, electric power companies that are currently considering building IGCC units say they want to gain experience with a technology that some day may need to be deployed in order to capture and store CO_2.

In short, coal and natural gas do not compete for the same market segments; instead the substitution of natural gas capacity for coal capacity (or vice versa) takes place on the margin between market segments. If it is profitable to add new coal capacity (say, because of higher gas prices), then more coal capacity stacked on the LC will increase the switch point H_{Base}, expanding the base-load segment until coal just breaks even again.

If it becomes unprofitable to build new coal units (say, because of a new carbon charge), then H_{Base} will decrease resulting in a larger shoulder segment, more NGCC investment, and a higher electricity price that returns coal investment again to break even status, albeit at a lower level of coal investment. Further, a higher electricity price will raise the eventual market share of renewable energy and, hence, increase the rate at which it penetrates the market given by the logistic equation.

3 Economy-wide effects

Climate policies adopted in the electricity sector are anticipated to have effects that will reverberate throughout the whole economy. A carbon price in the electricity sector raises the costs of producing electricity and causes investment in the electricity sector to be altered. In turn, price and investment changes in the electricity sector will spill over into, and influence, other sectors. In this section, we describe how a carbon price affects investment and output in the electricity sector and the rest of the economy.

3.1 SGM

The full investment story in SGM involves allocating capital at three levels: allocating investment across specific electric generating technologies; allocating investment across production sectors; and determining total investment in the economy. The earlier discussion of the electricity sector in SGM described how the logit sharing mechanism is used to divide investment between different electricity generating technologies as a function of levelised cost.

Here we describe the next level up in the investment story and discuss the procedures used to allocate investment among production sectors. A production sector is defined for every unique product in SGM, for example, electricity. Subsectors (technologies) represent different ways to make that product. The key to understanding sector-level investment in SGM is the rate of return on new capital. Investment in each production sector is a function of the rate of return; investment moves toward sectors with high rates of return and away from sectors with low rates of return.

The rate of return on capital in each sector is expressed as an expected profit rate, which is equal to the discounted value of revenue less variable costs for an investment over its lifetime, divided by the purchase price of capital. If the expected profit rate equals one, that means a capital expenditure is expected to just break even. Because of discounting, the expected profit rate moves in the opposite direction of an economy-wide interest rate.

When a carbon price is introduced, the price paid for fossil fuels will increase, and, *ceteris paribus*, the expected profit rates will fall in sectors that use fossil fuels, and investment will move away from carbon-intensive sectors. Since the capital stock in SGM is vintaged, production occurs from the old existing vintages of capital as well as from the new capital that results from current period investment. This means that the full response to a change in relative prices plays out over several years as old vintages are retired and replaced by new capital designed for the new set of relative prices.

The overall level of investment in the economy is determined by the clearance of the capital market. Savings is supplied by a representative household and corporations through savings supply functions that are increasing functions of the interest rate. The demand for investment capital is a decreasing function of the interest rate, and the capital market is brought into equilibrium through adjustment of the economy-wide interest rate.

When a carbon price is introduced, there is an increase in the cost of electricity which leads to decrease in electricity demand, and therefore less electricity is generated. Because of the carbon price, electricity and other energy carriers are more expensive for all sectors of the economy and there is a general substitution of capital, and other inputs to production, for energy. The impact on sector-level investment is the combined result of

two opposing drivers: a decline in output and the substitution of capital for energy. In the electricity sector, the decline in output dominates the input substitution effect and investment therefore declines. Other production sectors are less carbon-intensive and the decline in output is much smaller. In these sectors, investment could either increase or decrease, depending on whether the input substitution or scale effect dominates.

With a carbon price, there is an overall loss of output in the economy. Two measures of a change in economic output, in response to a carbon policy, are available from SGM. The first is a direct calculation of the change in Gross Domestic Product (GDP) between a base case scenario and a policy scenario. The second measure is the area under the MAC curve for carbon. Real GDP is measured in SGM as a Laspeyres quantity index, with base-year prices used as weights. This measure is easy to calculate and is built up from individual components for household consumption, government consumption, investment, and international trade.

A MAC curve can be constructed by exercising the SGM at various carbon prices and plotting the carbon price (vertical axis) against the quantity of reduced carbon emissions (horizontal axis). An approximation to the area under the MAC curve is calculated as one-half times the carbon price times the quantity of reduced emissions. The area under the MAC curve is essentially a deadweight loss calculation. However, this measure can underestimate the loss in economic output if there are pre-existing tax distortions in the economy. Therefore, in practice, the loss in real GDP is often greater than the area under the MAC curve.

3.2 AMIGA

AMIGA also links electricity sector impacts to investment, both in the electricity sector itself and economy-wide. For example, suppose that in AMIGA there is a shift to the right for electricity sector investment (greater demand) due to the carbon charge. The increased investment is needed to replace older, less-efficient power plants and to expand relatively clean natural gas and renewable generation capacity.

In response to increased investment in the electricity sector as a result of the carbon charge, some investment outside of the electricity sector will be 'crowded out' and credit for households will be less available. In market equilibrium, the supply of savings must equal the market demand for investment. Based on standard economic micro-foundations, the market demand for investment equals the horizontal summation of the investment functions for all the capital goods represented in the model. The AMIGA model represents capital stocks for a large number of energy supply technologies (such as those described here for electricity generation), end-use energy demand technologies (such as personal vehicles, freight transportation vehicles, buildings, appliances, and electrical equipment and lighting), and other sector production capital.

To restore market equilibrium, other investments will slightly decrease. The implications for the rate of economic growth of a decrease in the non-electric sector investment can be seen from the standard capital stock accumulation equation:

$$x_{t+1,i} = (1-\delta)x_{t,i} + I_{ne} \tag{3}$$

where $x_{t,i}$ is the stock of the non-electric sector capital factor of production, δ is the depreciation rate and I_{ne} is non-electric sector investment. Like SGM, the AMIGA model also uses the CES production function. As implied by the production function,

slower growth in capital stocks will slow output growth rates in the non-electric sectors of the economy, which will ultimately lower overall GDP.

Higher energy prices for electricity ripple through the economy and in turn induce other price adjustments. Growing sectors of the economy must pay competitive factor prices to attract capital and labour into their sector. As a result, some of the incidence of higher energy costs falls on labour wages. These relative price effects do not necessarily have a significant impact on real GDP, but there may be a small but noticeable impact on the distribution of income between labour and capital.

4 Base Case

One of the key goals of this exercise is to standardise key input assumptions between the two models so that we may gain insights by isolating how each model's projections differ due to their essential structural characteristics. Thus, a common Base Case is developed as an initial step in this effort.[6]

In developing the Base Case, key parameter representations of cost and performance characteristics for major electricity generating technologies are standardised between the models. These include heat rates, capital costs, and variable costs for PC plants, NGCC plants, integrated gasification and combined cycle plants, and wind turbines. If a parameter estimate varies significantly between the models, outside data sources are consulted (e.g., assumptions in the Annual Energy Outlook 2004, the Integrated Planning Model of ICF, Inc.) and a judgment is made as to what standardised assumption should be used for this exercise. Table 1 shows selected cost and performance assumptions for all electricity generating technologies in each model.

Table 1 Electricity sector cost and performance assumptions

	2010				*2020*			
	Capital costs (2000$ per kW)		*Heat rate* (Btu per kWh)		*Capital costs* (2000$ per kW)		*Heat rate* (Btu per kWh)	
Technology	*SGM*	*AMIGA*	*SGM*	*AMIGA*	*SGM*	*AMIGA*	*SGM*	*AMIGA*
Wind (onshore)	1005	*	–	*	995	*	–	*
Wind (offshore)	1200	*	–	*	1200	*	–	*
Solid biomass	1975	*	–	*	1936	*	–	*
Oil-fired	500	*	10,767	*	526	*	10,767	*
Waste combustion	2000	1515	–	–	2000	1485	–	–
Nuclear	1000	1553	–	–	1000	1522	–	–
Hydro Genrn	1000	1802	–	–	1000	1766	–	–
Wind class 6 & up	*	1028	*	–	*	988	*	–
Wind class 5	*	997	*	–	*	958	*	–
Wind class 4	*	944	*	–	*	907	*	–

Table 1 Electricity sector cost and performance assumptions (continued)

	2010				*2020*			
	Capital costs (2000$ per kW)		*Heat rate* (Btu per kWh)		*Capital costs* (2000$ per kW)		*Heat rate* (Btu per kWh)	
Technology	*SGM*	*AMIGA*	*SGM*	*AMIGA*	*SGM*	*AMIGA*	*SGM*	*AMIGA*
Wind local DG	*	1049	*	–	*	1008	*	–
Central Solar	*	1154	*	–	*	1109	*	–
Photovoltaic	5435	1993	–	–	5327	1915	–	–
Geothermal	1200	2119	–	–	1200	2077	–	–
NGCC	625	625	7524	7524	613	613	7376	7375
Peaker turbines	500	411	8685	8665	500	403	8685	8665
Pulverized coal	1150	1147	9917	9900	1150	1147	9721	9704
IGCC coal 1	476	1476	8672	8672	1447	1447	8500	8500
IGCC pet coke	*	1512	*	9874	*	1482	*	9678
IGCC biomass	*	1579	*	10,279	*	1548	*	10,075
NGCC CCS	1135	*	8671	*	1113	*	8500	*
Pulverized coal CCS	1996	*	10,515	*	1996	*	10,307	*
CCS coal IGCC	1961	1861	10,128	12,233	1923	1824	9928	11,990
CCS pet coke IGCC	*	1987	*	12,549	*	1948	*	12,300
CHP coal	*	1441	*	14,851	*	1413	*	14,556
CHP gas oil	*	721	*	13,861	*	706	*	13,586
CHP Renewable	*	1060	*	–	*	1039	*	–
Small generators	*	318	*	12,871	*	312	*	12,615
Bldg PV	*	1993	*	–	*	1915	*	–

Neither model includes all technologies. An asterisk (*) indicates that the model does not represent the specific generating technology listed. A dash (–) indicates a non-fossil technology for which there is no 'heat rate'.

Besides the characteristics of the electricity generating units, another key factor influencing trends in the electricity sector is fossil energy fuel prices. To standardise fuel prices in the Base Case, both models utilised price paths for coal, crude oil, and natural gas from the DOE's Annual Energy Outlook 2004 forecast through the 2025 period.[7]

Additionally, the generation shares for the different electricity generating technologies are benchmarked to the AEO 2004. This is accomplished in different ways in the two models. AMIGA has a relatively detailed bottom-up electricity sector with

electricity generating technologies dispatched to satisfy a LC. Thus, the generation shares that result from the dispatch model, given the assumptions about costs and fuel prices, are roughly equivalent to the generation shares from AEO 2004. SGM, on the other hand, has a more top-down electricity sector with no model of the dispatch of electricity. Therefore, in SGM the b_j parameters for each technology must be set in order for the resulting generation shares to approximate those from AEO 2004.

With a program to control CO_2, the demand for natural gas in electricity production would increase, but the demand for natural gas elsewhere in the economy would likely decline. Therefore, overall consumption of natural gas does not vary as much as coal consumption with a CO_2 control program. In fact, economy-wide consumption of natural gas could move in either direction with a CO_2 control program. In this effort, we standardised the responsiveness of natural gas supply to price between the two models.

Next, we 'tune' the SGM and AMIGA projections to roughly match broader, more aggregate forecasts of the US economy. For this exercise, aggregate measures that are matched include GDP, primary energy consumption, electricity demand, and CO_2 emissions (both in the electricity sector and economy-wide).[8] Projected trends from DOE's Annual Energy Outlook 2004 are the basis for developing these more aggregate forecasts.

Some model characteristics could not be matched in the time frame of this exercise. For example, AMIGA includes combined heat and power and small generators while SGM does not. SGM includes commercial biomass and carbon dioxide capture and storage while AMIGA does not. Geothermal is endogenously determined in AMIGA while in SGM, geothermal is exogenous. Ideally, with more time, these individual power technologies would be built into the models.

Another major difference between the two models is power plant lifetimes. In SGM, all power plant lifetimes are 20 years, which is recognised by the SGM modelling team to be too low, but was chosen in lieu of modelling the retrofitting of existing plants.[9] In AMIGA, plant lifetimes are modelled at 40 years.

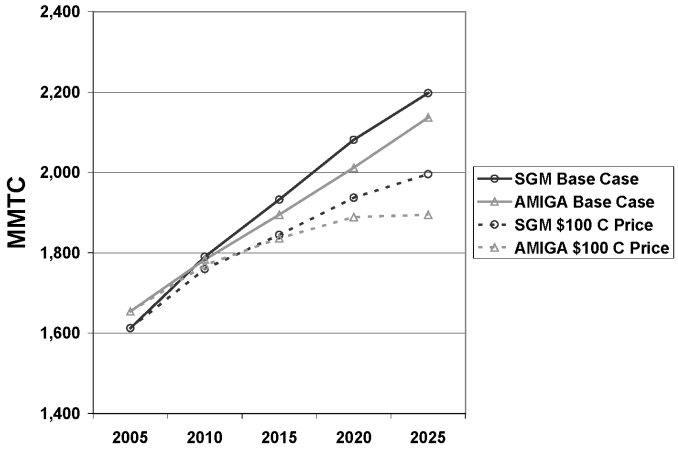
5 Results

In this section, we summarise some of the key results from the model comparison exercise. We begin with a hypothetical carbon charge in the US electricity sector implemented at \$50 in 2010, rising in 2015 to \$100, and staying at \$100 thereafter, labelled 'Policy Case' below.

5.1 Carbon and fuel market impacts

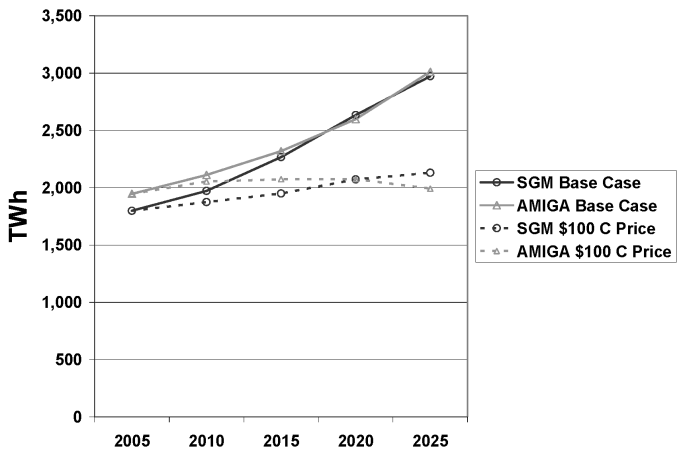
US economy-wide carbon emissions in the Base Case and Policy Case from 2005 to 2025 are shown in Figure 4. With the carbon charge, carbon emissions fall in SGM by roughly 5.6%, 87 Million Metric Tons of Carbon (MMTC), in 2015, and 9.2% (202 MMTC) in 2025. For AMIGA, carbon emissions fall by less in the 2015 timeframe and by a slightly larger amount in the later portion of the forecast period – in 2015, by 3.2% (59 MMTC) and in 2025 by roughly 11.7% (248 MMTC). One reason for this difference may be the longer plant lifetimes in AMIGA, which should cause AMIGA to be less responsive to a carbon charge in the short run.

Figure 4 Projected US economy-wide carbon emissions



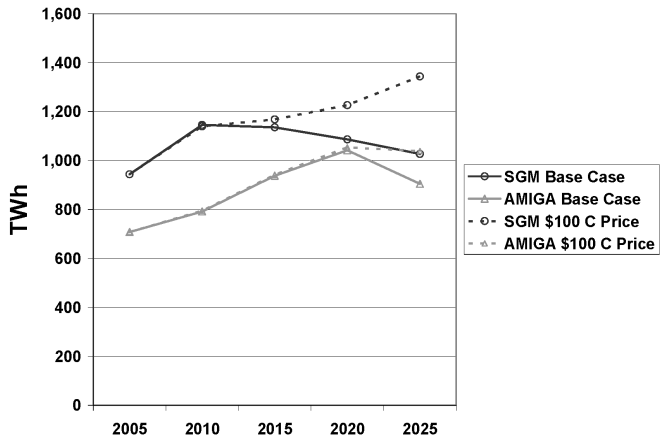
Carbon emissions reductions are achieved by a variety of responses in the US electricity sector. As anticipated, the reduction in carbon emissions primarily stems from switching from coal to natural gas. Figure 5 shows changes in US electricity generation from coal throughout the forecast period in both models. In SGM, electricity generation from coal falls by 14% (347 TWh) in 2015 and 32% (843 TWh) in 2025. Electricity generation from coal in AMIGA falls by roughly the same amount, 10.6% (245 TWh) in 2015 and 33.9% (1019 TWh) in 2025.

Figure 5 Projections of coal-fired electricity generation



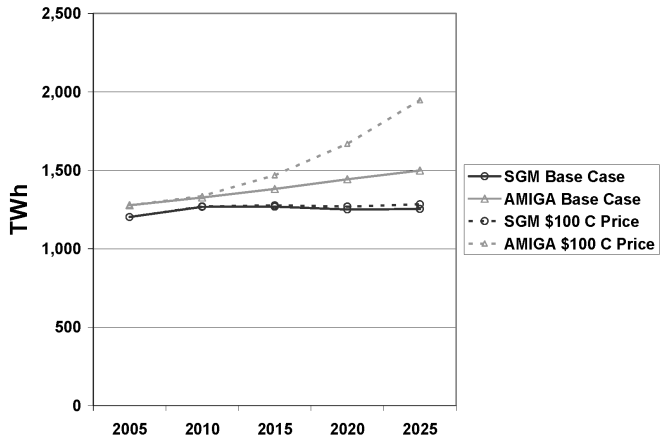
Coal's loss in electricity generation is partially offset by natural gas's gain. Figure 6 shows the increase in electricity generated from natural gas from the carbon policy in the two models. We see some divergence in results here. In SGM, natural gas's market share increases by 2.8% (32 TWh) in 2015 and 30.9% (317 TWh) in 2025. In AMIGA, electricity generation from natural gas shows only a 4 TWh increase in 2015. By 2025, electricity derived from natural gas increases by 134 TWh, or roughly 14.8%, significantly less than in SGM.

Figure 6 Projections of natural gas-fired electricity generation



What, then, explains the larger reduction in carbon emissions from AMIGA in comparison to SGM by 2025 and the smaller share of natural gas in AMIGA? AMIGA shows a much larger increase in the use of alternative electricity sources than SGM. Figure 7 shows alternative generation in the two models through 2025. These sources include wind, small generators, geothermal, combined heat and power, nuclear power, and hydro. Since nuclear power and hydro are exogenously determined, their contribution to electricity generation does not change in response to the carbon policy.

Figure 7 Projections of electricity generation from alternative sources



As can be seen by viewing Figure 7, AMIGA has a comparatively large increase in electricity generation from these sources. In 2015, alternative generation increases by 77 TWh or 59%. By 2025, alternative generation increases by 369 TWh or 189%. In SGM, alternative electricity generation is essentially flat, with very little pick up in its share of electricity supply.

What accounts for the different response of the models with respect to alternative generation? In part, AMIGA has more abatement options than SGM, such as combined heat and power, endogenous geothermal, and small generators. But this only explains part

of the difference. In AMIGA, wind power increases dramatically in the Policy Case. By 2025, annual investment in wind power in the Policy Case is roughly $11.1 billion. In comparison, annual investment in wind power in the Base Case is $625 million. (To place this in context, AMIGA projects annual investment in new, traditional PC plants in the Policy Case will be $9.7 billion in 2025.)

The same pattern is exhibited in many of the other alternative generation sources. For example, annual investment in small generators increases from roughly $2.4 billion in 2025 in the Base Case to $8.7 billion in the Policy Case. Annual investment in fossil combined heat and power increases from $612 million in the Base Case in 2025 to $2.1 billion in the Policy Case. Annual investment in geothermal technology increases from $677 million in 2025 in the Base Case to roughly $2.4 billion in the Policy Case. In AMIGA, these technologies successfully compete away market share from natural gas-derived electricity, limiting natural gas' penetration into the electricity market.

The obvious question raised is: how does the structure of the two models influence these alternative technology choices such as wind power, combined heat and power, etc.? In SGM, the logit sharing equation uses the b_j's to constrain alternative technologies such as wind power to match historical experience and allows wind to compete in the future based upon costs compared with other electricity generating technologies.

AMIGA, on the other hand, assumes that wind will compete in the long run based on its projected cost compared with other electricity generating technologies, such as fossil power plants including, in the Policy Case, a carbon charge. This, in effect, becomes the long-run market potential for a technology such as wind power. AMIGA then uses a logistic function calibrated to past historical experience to allow wind penetration to increase over time to its long-run economic potential. The methodologies for the treatment of alternative generating sources are quite different in each model, leading to quite different results.

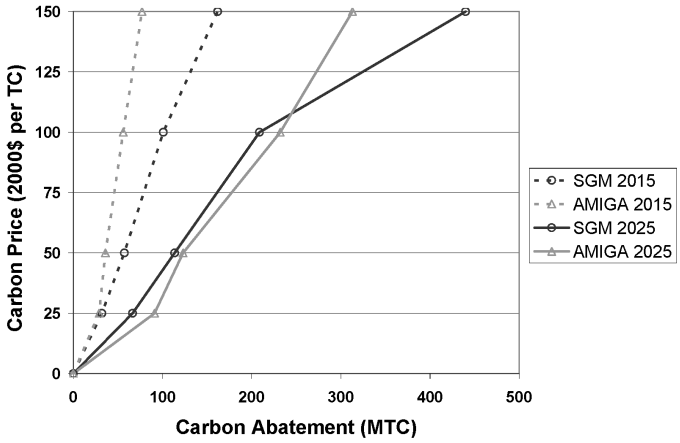
The last factor that influences carbon abatement is the fall in demand for electricity. In SGM, electricity demand declines by 5.7% (270 TWh) in 2015 and 8.8% (466 TWh) in 2025. In AMIGA, electricity demand falls by roughly 3% (141 TWh) in 2015 and by 5.8% (316 TWh) in 2025. In other words, SGM tends to have a slightly larger demand response to this carbon abatement policy experiment.

Both models also report changes in wholesale electricity prices with a Policy Case relative to the Base Case. These price increases are not expected to affect transmission and distribution costs which represent a substantial fraction of delivered energy costs, so that electricity consumers will not experience changes as great as the wholesale price changes. By 2025, SGM forecasts a 40% increase in wholesale electricity prices, compared with a 25% increase forecast by AMIGA. These price increases reduce demand for electricity by nearly 9% in SGM and 6% in AMIGA.

5.2 MAC comparison

One way to summarise and compare the carbon abatement opportunities in both models is by developing MAC curves. These MAC curves map the costs of reducing emissions of CO_2 from the electricity sector compared with a Base Case.[10] In Figure 8, we show the MACs for AMIGA and SGM for the years 2015 and 2025 for constant carbon prices of up to $150/ton of carbon abated.

Figure 8 Comparison of Marginal Abatement Cost (MAC) curves



To summarise a comparison of the MACs, SGM predicts more abatement for a given carbon charge in 2015 than AMIGA, but by 2025 the two models have roughly similar MACs. A variety of factors influence near-term abatement options in the models. SGM achieves more abatement due to its higher responsiveness of electricity demand to price and shorter plant lifetimes.

A central difference between the two models is that carbon abatement is achieved in different ways. For SGM, most of the carbon abatement for carbon prices less than $100/ton of carbon is achieved by switching to natural gas from coal in the electricity sector. Above the $100 carbon price, carbon dioxide capture and storage technologies play a key role in carbon abatement. For AMIGA, while switching to natural gas plays a significant role in carbon abatement much like SGM, alternative electricity generating sources are also significant contributors to the carbon abatement underlying the MAC.

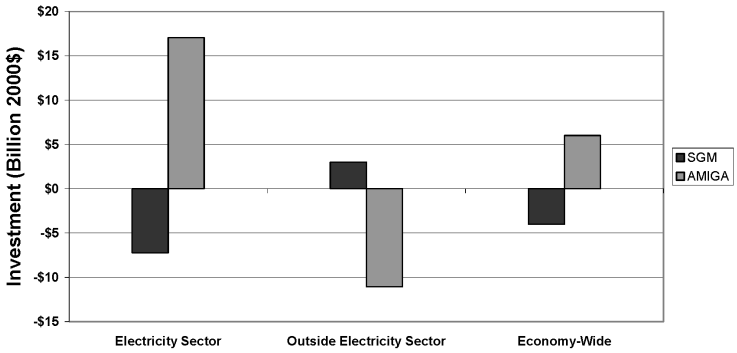
5.3 Economy-wide implications

Given that both models have CGE structures that highlight the interlinkages of the economy as a whole, they have the capability of tracing the ripple effects of a carbon abatement policy throughout the economy. Consider the impacts of a carbon policy on investment by 2025. Electric sector investment increases relative to the Base Case in AMIGA, whereas electric sector investment decreases in SGM. There are three principal reasons for this difference. First, the impact on electricity price is somewhat greater in SGM, leading to a greater reduction in electricity demand. Second, the natural rate of power plant capital turnover is much faster in SGM than in AMIGA, implying less inherent rigidity in SGM. Since the AMIGA model assumes long life expectancies for coal-based power plants, accelerated retirement of these plants requires early replacement investments that are not needed in the Base Case. Third, the dominant choice of a future, lower-carbon technology is different in the two models; AMIGA tends to build more capital-intensive, renewable technologies, whereas SGM tends to build less capital-intensive natural gas generators.

In AMIGA, investment increases in the US electricity sector by roughly $17 billion by 2025 (See Figure 9). This increase in investment raises interest rates, causing investments outside of the electricity sector to be ‘crowded out’. Investment outside of

the electricity sector falls by roughly $11 billion in 2025. On balance, however, AMIGA projects total investment in the US economy to be higher by roughly $6 billion in 2025.

Figure 9 Response of investment in SGM and AMIGA in 2025 to a carbon price of $100



In comparison, investment in the US electricity sector in SGM is estimated to fall by roughly $7 billion by 2025. Investment in SGM is the net result of a scale effect and input substitution effect. For any carbon policy, output declines in SGM, but electricity output falls more than output in other production sectors. However, higher energy prices create incentives for substituting capital for energy, as inputs to production, and this tends to increase investment. The scale effect dominates in the electricity sector but not in sectors outside of electricity.

GDP losses from the carbon policy are generally higher in SGM than AMIGA. By 2015 in SGM, GDP is 0.06% ($9 billion) lower in the Policy Case as compared with the Base Case. By 2025, GDP is 0.12% ($23 billion) lower in the Base Case compared with the Policy Case. In AMIGA, GDP is unaffected in 2015 by the carbon policy and GDP falls by just –0.005% ($1 billion) in 2025 between the Base and Policy Case. Even though the GDP impact is larger in SGM compared with AMIGA, the impacts are small relative to the size of the overall economy.

6 Conclusions

This effort has sought to delve into the inner working of two models – SGM and AMIGA – and highlight the consequences of different modelling approaches and structures on the estimation of climate change policy results. We show that different assumptions about how technology choices are made in the electricity sector in response to a carbon charge can lead to differences in estimates of environmental, fuel market, and economy-wide impacts. For example, how the two models structure technology choice decisions in renewables and other alternative forms of electricity production can have significant implications not only for environmental results and fuel markets but also for economy-wide variables, such as investment and total economic output.

Efforts of this type should be undertaken with other models, and in more depth. Results from these comparisons lead to better understanding of climate economic models and of the types of results that they produce. If the differences among models can be better understood, improvements in the models may be made and policy makers will be better informed by the insights provided by the models.

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Notes

[1]Edmonds *et al.* (2004) provide an overview of SGM, Fawcett and Sands (2005) give a detailed description of the model structure and theory, and Sands and Fawcett (2005) document the data and parameterisation of the model.

[2]Hanson and Laitner (2004) and Hanson *et al.* (2003, 2004) provide further descriptions of the AMIGA model.

[3]Notice that we examine price policies but no effort is made to examine so called 'non-price' policies (e.g., standards, research and development activities, etc.). Examination of 'non-price' policies is a considerably more complex task and beyond the scope of this exercise.

[4]See Clarke and Edmonds (1993) for an overview of the use of a logit sharing mechanism for modelling energy technologies, and Sands (2004) for a discussion of the dynamics of carbon abatement in SGM.

[5]This is the unit cost function for a CES production function of the form:

$$q = \alpha_0 \left[\sum_{i=1}^{M} (\alpha_i x_i)^{\rho} \right]^{\frac{1}{\rho}}$$

where q is the quantity of output; i is an index over inputs; M is the total number of inputs; x_i is the factor demand for input i; and ρ is equal to $(\sigma - 1)/\sigma$.

[6]Both models are reasonably flexible and have developed procedures through time to 'tune' their Base Case forecasts to alternative forecasts. Models used by the government are oftentimes required to calibrate their Base Case to be consistent with government policy.

[7]The crude oil and natural gas price paths in SGM are exogenously set equal to the prices forecasted in AEO 2004, while the coal price is determined endogenously. In AMIGA, the fossil energy prices are determined from a set of dynamic supply curves, the intercepts of which are adjusted to calibrate to the AEO 2004 fuel price projections.

[8]For SGM, a variety of parameters are varied to match the NEMS/AEO forecasts. GDP can be 'tuned' by adjusting an aggregate labour productivity factor; technical change rate parameters for primary fuels across end-use sectors can be used to tune primary energy consumption; electricity demand can be tuned by adjusting technical change rate parameters for electricity across end-use sectors; and, if the previous variables are tuned to an outside forecast, then CO_2 emissions will fall in line. Similarly, the AMIGA model's labour productivity rates can be adjusted to calibrate to a reference case GDP path.

[9]This assumption in SGM is in the process of being updated in a detailed follow-on effort.

[10]While not part of this exercise, it is worth noting that including offsets from non-CO_2 gases and terrestrial sources would substantially increase the amount of abatement that could be achieved for a given carbon price.