APPENDIX.
CRA INTERNATIONAL'S
MRN-NEEM INTEGRATED MODEL
FOR ANALYSIS OF US GREENHOUSE GAS POLICIES

1.1. OVERVIEW: AN INTEGRATION OF A TOP-DOWN AND A BOTTOM-UP MODEL

CRA International has been using two distinct classes of models to analyze carbon abatement policies: (i) a general equilibrium (or top-down) model and (ii) an investment and technology decision-based linear programming (or bottom-up) model. These classes of models, in general, are analyzed by employing two distinct modeling paradigms: top-down and bottom-up analysis.[1] The top-down models are the standard economic framework for analyzing economy-wide policies and are the most commonly used tool for assessing macroeconomic impacts. In this modeling framework, an economy is completely represented. The production sectors, final household demand, and government taxation and spending are represented - thus, economy-wide relationships are captured. But most importantly, the model is based on rigorous microeconomic theoretical foundations. Under (carbon) policy scenarios, all agents in the model respond to price changes (including changes in energy prices and products that utilize energy in their manufacture) and the inter-linkages within the model enable it to take into account a complete set of feedbacks within the economy. The top-down models can also be easily expanded to include multiple regions linked by trade. With such flexibilities, top-down models are suitable for simulating a wide variety of policies, such as the impact of energy policies, trade policies, public finance policies, and many other real world policies, to determine who wins and who loses under these policies.[2] The MRN model falls under this category.

Bottom-up models on the other hand are used to find the choice of least-cost technology that satisfies a portfolio of policy measures. These models involve detailed characterization of one aspect of the economy. In particular, models of the electricity sector constructed at the unit level with a menu of costs for current and future technologies are often employed to study the impact of environmental policies on this sector. The NEEM model falls under this bottom-up category.

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[1] International Panel on Climate Change (IPCC), 1996.

[2] General equilibrium models should not be viewed as a forecasting tool. The results depend upon how the business-as-usual (BAU) case is constructed against which the policy is simulated. The BAU outlook entirely depends upon the modeler's assumptions that go into constructing it. Results from general equilibrium analyses are grounded in the BAU assumptions and hence should at best be interpreted as conditional forecasts.

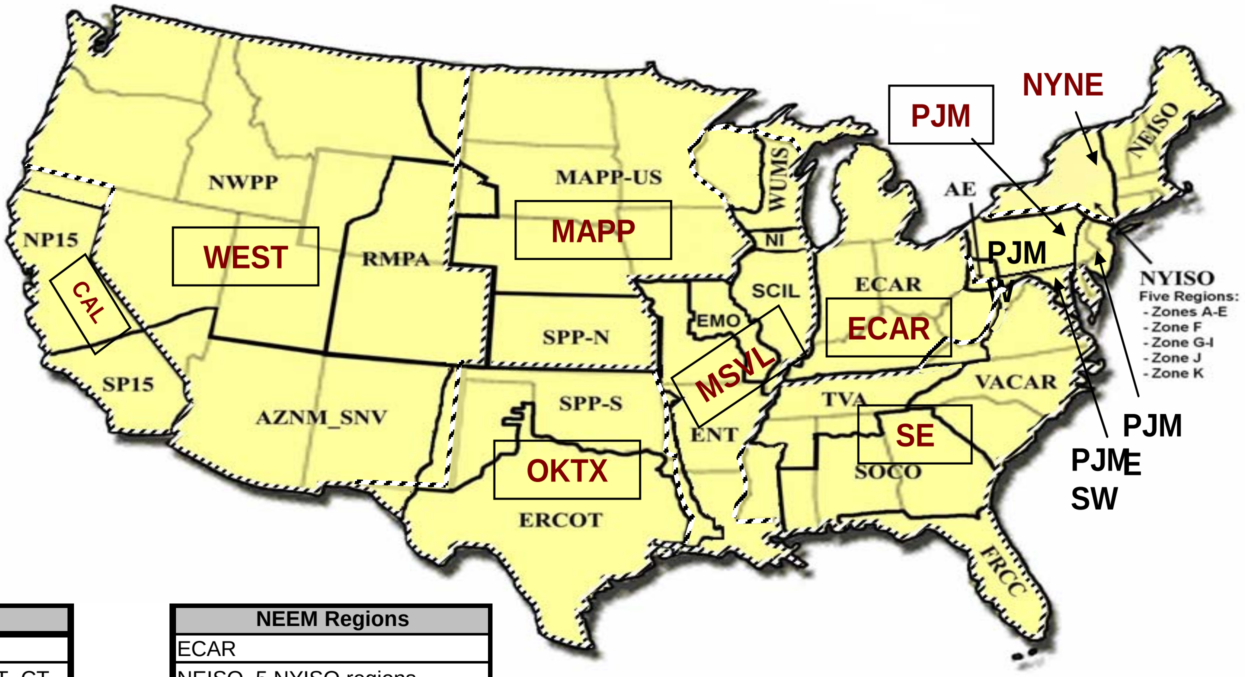
The two approaches are very distinct in both model structure and their representation of the energy-economic system. The top-down model's representation of the economy is complete at a macro-level but lacks detail regarding specific technologies. Specific technologies are best described from an engineering perspective which general equilibrium models are unable to represent. In the top-down model, an economic system is represented by production sectors where preferences and technologies are represented by smooth functions. All agents in the model interact to capture economy-wide effects. All agents in the model are forward-looking, rational optimizers. In contrast, the bottom-up model represents only a portion of the economy (e.g., the energy system or the electricity sector). The bottom-up model is incomplete but this weakness is compensated by the richness of its technology representation. In addition, the sectoral detail encompasses each and every generation unit within the electric sector - this adds realism for actual simulation for practical application. However, despite these strengths, bottom-up models do not fully represent the economy and fail to account for macro-economic feedbacks from the rest of the economy. Thus, bottom-up models cannot be used for macro-economic analysis.

A carbon policy's effects ripple through the entire economy, so serious analysis of a carbon policy requires macro-economic analysis. But carbon policy will pointedly affect the electric sector, so the use of a bottom-up model is desirable. Therefore, top-down and bottom-up models have a complementary role to play in policy analysis. If coupled appropriately, they can generate a wide-range of detailed results that are consistent across the two models. The weakness of the top-down model is well compensated by the strength of the bottom-up model and visa-versa. Hence an integrated model of a top-down and bottom-up model is an ideal model that provides the best of both models. CRA International integrated its two models - MRN and NEEM - into a single MRN-NEEM model to provide a unique and consistent approach for U.S. carbon policy analysis.

An over-arching difference between the two models is regional detail and definition. Figure 1 shows the relationship between the NEEM and MRN regions. There are 27 U.S. NEEM regions but only 9 MRN regions.

In the following sections, the MRN-NEEM model and the methodology used to integrate the two models is described. The MRN model is discussed in Section 1.2, followed by discussion of NEEM in Section 1.3. To conclude, Section 1.4 provides a somewhat technical description of the method used to integrate the two models.

Figure 1. Map Showing NEEM and MRN Regions



MRN Region	Description	State
ECAR	ECAR	MI,IN,OH,KY,WV
NYNE	NY and NEISO regions	MA, ME, NH, NY, RI, VT, CT
MAPP	MAPP-US	ND,SD,NE,KS,MN
PJM	PJM	PA,MD,DC,NJ, DE
CAL	California	CA
West	West except California	WA,OR,AK,HI,ID,MT,NV,UT, CO,WY,AZ,NM
SE	South East	MS,AL,TN,GA,SC,VA,NC,FL
OKTX	Oklahoma and Texas	TX,OK
MSVL	Mississippi Valley	IA,IL,MO,AR,LA,WI

NEEM Regions
ECAR
NEISO, 5 NYISO regions
MAPP-US,SPP-N
AE,PJM
NP15, SP15
NWPP,RMPA,AZNM_SNV
SOCO,FRCC,TVA,VACAR
SPP-S,ERCOT
WUMS,NI,SCIL,EMO,ENT

1.2. MULTI-REGION NATIONAL (MRN) MODEL

1.2.1. Overview of MRN Model

MRN is a top-down, computable general equilibrium (CGE) model of region-specific impacts and regional interaction in the U.S. economy. The CGE tracks every dollar that is spent through the economy to reduce carbon emissions, accounting for the economic gains in those sectors that provide the goods and services that result in emissions reductions, as well as the economic costs to those who incur these added expenditures. In addition, the negative impacts associated with declining demand under higher, policy-induced prices are captured. The model also accounts for any changes in the distribution of wealth that result from the combined impact of emissions control spending and the disposition of the wealth associated with newly created allowances. The results of a model run thus reflect the *net* impact to the U.S. economy after all the impacts on the winners and losers under a proposed policy have been estimated.

The model also assumes that implementation of a policy such as a carbon emissions cap will occur in a least-cost fashion with fully-functional, competitive product and allowance markets. The only limits imposed on the efficiency of a cap-and-trade market are those that are directly specified in a policy or Bill, such as when some sectors are not covered by the proposed cap scheme (even if placed in the offsets category). Leakage of some economic activities outside of the U.S. is also estimated for sectors that face competitors in other countries that do not have their own emissions caps (or have weaker caps).

The model works with perfect foresight of future prices and policy requirements. This means that the model does not include any costs due to uncertainty and “surprises” that will probably also be associated with compliance with a new policy. It also captures only a long-run equilibrium in all of the markets, and thus does not include any of the costs of an overly rapid shift in markets due to imposition of a new policy.

The CGE model solves for production levels, trade, relative prices, income, and consumption by accounting for technological as well as behavioral responses to changes in policy. The equilibrium is fully dynamic, meaning that investment decisions determine the future capital stock, which in turn determines future income and consumption. Furthermore, decisions to consume or invest are taken with correct expectations about future policy and opportunities (i.e., perfect foresight). Investment today requires foregoing consumption of current income. Consumer decisions maximize utility inter-temporally, which implies that an optimal financial trade-off is made between consumption today and consumption in the future.

Many of the impacts of policies to reduce carbon emissions indirectly increase the cost of production and consumption, and this has effects on the demand for all commodities. For example, a limit on the quantity of allowable emissions from electric utilities will result in higher electricity prices. Higher electricity prices will then raise production costs throughout the economy, but especially in sectors that use electricity-intensive production processes. As all sectors adjust their production processes to be optimized under post-policy prices, there are changes in demand for labor, materials and commodities, capital, and different types of fuels and primary energy sources.

MRN only explicitly models the economy and energy sector in the U.S., but it does account for foreign imports and exports. Data that characterize the interrelationships of commodity uses within the economy therefore are of primary importance in quantifying the impacts from alternative carbon regulations. As a starting point for characterizing the inputs and outputs of commodities in the U.S. economy, MRN uses a Social Accounting Matrix (SAM) developed for each state by the Minnesota IMPLAN Group, Inc. (MIG). The IMPLAN database represents the activities in 509 sectors for all 50 states and the District of Columbia. CRA adjusts the original SAM data to make them consistent with state-level energy data from the U.S. Energy Information Administration (EIA), which are more accurate than the corresponding IMPLAN data with respect to energy flows in the U.S. economy. The SAM that results from the combination of IMPLAN and EIA data exactly matches the intensities of commodity use for the modeled production and consumption sectors for any regional aggregation of states. In addition, the SAM completes the circular flow with an account of factor incomes, household savings, trade, and institutional transfers.

Conceptually, the SAM represents a “snapshot” of the economy at the current point along a dynamic growth path. MRN simulates the dynamic growth path into the future in the absence of major changes to policies that are “on the books” today. This initial growth path is known as the “business-as-usual” case, or BAU. In other words, the initial snapshop is for a single year but the BAU case is a forecast over many years. Calibration of the BAU case from the initial snapshot provided by the SAM is completed by incorporating growth forecasts for industries, population, and carbon emissions.

The regional detail of MRN can be specified at any level of disaggregation down to the state level, depending on the needs of the analysis.[3]

Since carbon emissions are highly correlated with energy use, all the important energy sectors contained in the detailed SAM are represented as individual sectors in MRN.[4] CRA

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[3] In contrast, the NEEM model divides the U.S. into 27 separate regions. This allows greater specificity in assessing impacts to coal markets and allowance markets. Regional gas price differentials are also captured in the NEEM portion of the analysis, based on changes at the Henry Hub projected by MRN.

aggregates all of the remaining (non-energy) sectors in the SAM into five groups that capture the diversity in energy-intensity across all economic activities. MRN typically uses the ten production sectors in Table 1.[5] MRN also accounts for household energy uses, as well as all the productive sectors of the economy, so that MRN can correctly account for individuals' responses to higher fuel costs caused by carbon abatement policies. Importantly, personal transportation (i.e., automobile use) is included in the household energy uses, not in the transportation sector listed in Table 1.

Table 1: Typical MRN Model's Sectors

Energy Sectors	Non-Energy Sectors
Coal extraction	Agriculture
Oil and gas extraction	Energy-intensive sectors
Oil refining/distribution	Manufacturing
Gas distribution	Transportation services
Electricity generation	Services

MRN tracks carbon dioxide emissions (stated as metric tonnes of carbon-equivalent) from fossil fuel combustion and assumes that the costs of reducing other greenhouse gases are comparable to the cost of reducing carbon dioxide emissions. To incorporate carbon emissions in the model, an emissions permit is tracked for each of the three fossil fuel inputs (refined oil, natural gas, and coal). When there is a carbon cap, a limited, fixed number of emissions allowances is assumed available in each modeled year. If that limit is less than the BAU emissions level, a scarcity of allowances (i.e., when demand for allowances exceeds their supply) will exist. This scarcity increases the price on carbon (starting from zero) up to the point where demand for the allowances is reduced to the limit of their supply. Limiting the

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[4] Non-CO_2 greenhouse gas emissions from coal extraction and oil and gas extraction are not modeled explicitly. An (exogenous or user-defined) offset supply curve based on emissions reductions in these and other natural resource-based sectors (e.g., agriculture) is used to represent the cost of supplying offsets.

[5] Coal extraction and oil and gas extraction are assumed to consume zero fossil fuels.

number of allowances available imposes an emissions constraint, and the permit price reflects the marginal cost of abatement.

1.2.2. Basics of General Equilibrium Models

The top-down sub-model of the integrated MRN-NEEM model is tailored from CRA International's Multi-Region National (MRN) model. MRN is a forward-looking dynamic computable general equilibrium model of the United States. It is based on the theoretical concept of an Arrow–Debreu equilibrium in which macro-level outcomes are driven by the decisions of self-interested consumers and producers as they are in the real economy. The basic structure of CGE models, such as MRN, is built around a circular flow of goods/services and payments between households, firms, and the government, as depicted in Figure 2. Consumers are represented by a single household sector[6] in each region that maximizes utility subject to endowments of primary factors and all production sectors are assumed to be competitive with underlying technology exhibiting constant returns to scale. Households own and supply the factors of production (capital and labor) to firms that transform these factors into goods or services. Households receive payment from the firms for supplying factors of production (capital income and labor wages). Firms in the model maximize profit subject to technology constraints to determine the level of optimal production. Firms utilize the factors supplied by households and use intermediate inputs produced by other firms. Households consume goods and services using the wage (and capital) income from firms, while the firms receive payment for goods and services that are supplied to the market. Under the circular flow concept, there is a balance of goods, services, and payments across the economy.

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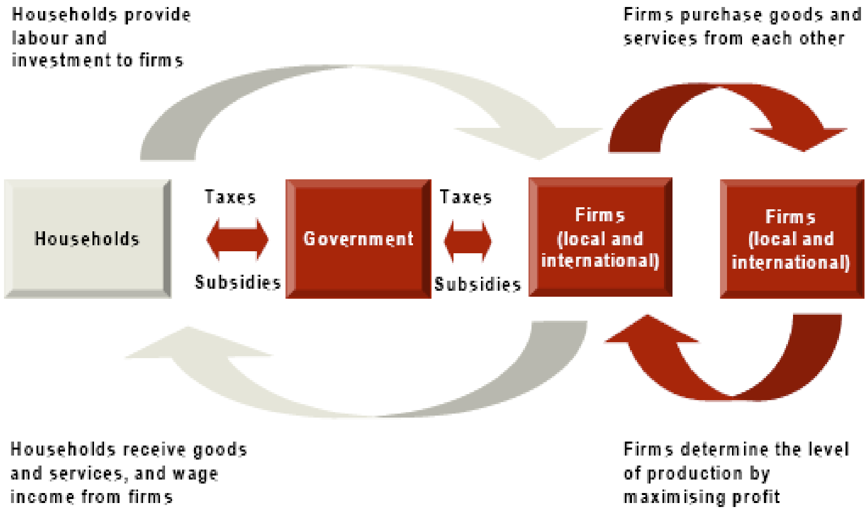
[6] The model can easily be extended to include multiple households differentiated by preferences over consumption bundles or income level.

Figure 2. Circular Flow of Goods and Services and Associated Payments



1.2.3. The MRN Model is a General Equilibrium Model

The theoretical basis for the version of MRN used in the integrated MRN-NEEM model is the same as that of the standalone MRN.[7] The only difference between the standalone MRN and the MRN sub-model of MRN-NEEM is the treatment of the sectors represented in the NEEM model. Since the NEEM model accounts for electricity and coal production in detail, MRN does not explicitly model these sectors. Thus, there are eight production sectors in MRN-NEEM rather than the ten production sectors shown in Table 1. Individual states are rolled up to create the regions. The model assumes a single representative household for each region, a federal government, and ten production sectors.[8] The production sectors in the model are disaggregated as listed below.[9]

Energy sectors:

- Crude oil and gas extraction.

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[7] The standalone MRN model is a self-contained model that represents all sectors of the economy.

[8] The Regional and Federal government budgets are balanced over the model's analysis period. This is true for both the BAU case and the policy scenario(s). Any deficits incurred in a particular year need not be the same between the BAU case and the scenario, as long as each is balanced over entire analysis period.

[9] Note that electricity generation and coal production are modeled in the bottom-up model (NEEM) in the integrated model.

- Oil refining and distribution,
- Gas distribution,

Non-energy sectors:

- Agriculture,
- Energy-intensive sectors,
- Manufacturing,
- Commercial transportation.
- Services,

Consumers are represented as a single representative household that maximizes lifetime utility subject to its lifetime budget constraint. Utility in a given time period is measured by the consumption of goods. The budget constraint equates the present value of consumption gross of tax to the present value of income earned in the labor market and the value of the initial capital stock minus the value of post-terminal capital.[10] In other words, consumers cannot consume more than the present value of their income and capital wealth. They typically will consume less than the present value of their income and capital wealth (in any year) in order to maximize utility over many years. Households optimally distribute wealth over the model horizon by choosing how much output in a given period to consume and how much to forgo for future investment.

As previously mentioned, two primary factors of production are supplied by the household sector: labor, which grows exogenously and is therefore an input to the model, and capital. In the model, depreciation of the capital stock depends on maintenance expenditures and vintage of the capital stock. The depreciation rate in the model is not assumed to be fixed. It is (endogenously) determined within the model and has an isoelastic relation with maintenance expenditure and capital stock. This captures the notion that the capital stock (equipment and machinery) is maintained and repaired during its life and its level of use will determine how much maintenance occurs. This subtle notion is generally ignored in other models. The dynamics in the model are partially controlled by implementing an adjustment cost in the capital stock.

As with the consumer behavior, the federal government also maximizes its model-horizon utility subject to a model-horizon budget constraint. The government collects tax revenues at

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[10] The input taxes are based on the marginal tax rate.

an average tax rate, purchases goods and services, and transfers income to the representative households in the model. The government maintains a balanced budget over the model horizon meaning that there is no change in the net foreign indebtedness over the time horizon of the model.

Firms in the model use capital, labor, energy, and material inputs to produce goods. Production of one good may require more of one input than the production of another good. For example, production of energy-intensive goods (e.g., aluminum) requires more energy inputs relative to the production of service goods. Moreover, embedded production is such that inputs are easily substituted in some cases but not in others. For example, switching between coal and gas inputs is much easier in producing electricity than in the production of energy-intensive goods because electricity generating stations are often designed with fuel flexibility in mind whereas production processes are usually less flexible..

The MRN model captures the substitutability of inputs for various sectors and technologies by employing a nested constant elasticity of substitution (CES) structure. In the MRN CES process, inputs are mixed at different tiers of the production tree to form composite goods – not unlike a cooking recipe. At the bottom of the production structure, coal and gas inputs are combined to form a coal-gas composite input which substitutes against electricity input. An energy composite of coal-gas-electricity is then combined with a capital-labor composite (value-added composite) input to form an aggregate energy-value-added composite. This composite is then combined with the rest-of-the-other-goods composite to produce a final commodity. The substitutability between inputs depends upon the assumed value of the elasticity of substitution and the initial share of the inputs. The higher the value of the elasticity of substitution, the easier it is to switch between inputs.

MRN is a national model and hence does not explicitly model other regions of the world. However, international trade is important in the real economy, so MRN roughly interacts with the rest of the world through simulated trade. International trade takes place in all goods except for crude oil. Crude oil in the model is treated as a homogenous good and is perfectly substitutable across all regions. All other goods are differentiated by their origin. That is, domestic and imported like-products are treated as imperfect substitutes. This is the classical Armington assumption referred to in trade economics. Imported goods and domestically produced goods are mixed to form an Armington aggregate good that is supplied to the domestic market for consumption and use in production. The value of the elasticity of substitution between the imported and domestic product influences the extent to which imported products can be substituted for domestic ones.

The model solves for production levels, trade, relative prices, income, and consumption by accounting for technological as well as behavioral responses to changes in policy. The equilibrium solution is dynamic, meaning that investment decisions determine the future capital stock, which in turn determines future income and consumption. Furthermore, since the households in the model are fully rational, decisions to consume or invest are taken with correct expectations or full knowledge of about future policy and opportunities.[11] Consumer decisions maximize utility, which implies that an optimal trade-off is made between consumption today and consumption in the future. Investment today requires foregoing consumption today.

The core component of the MRN dataset is based on the Social Accounting Matrix (SAM) developed by the Minnesota IMPLAN Group, Inc. (MIG) that represents the economic flows of 50 states of the U.S. and the District of Columbia for the year 2002. The SAM provides data on employment, industry output, value added, institutional demand, national input-output structural matrices (use and make tables), and inter-institutional transfers. This dataset provides a snapshot of the economy for each of the U.S. states. Although, the IMPLAN dataset has a detailed record of non-energy data, the data quality of the energy sector is lacking and inconsistent with the U.S. official data published by the U.S. Energy Information Administration (EIA). Therefore, the IMPLAN energy data have been replaced with energy data from the EIA's AEO. The energy and economic dataset has been calibrated such that the resulting input-output tables for each state balance and the energy values in the dataset are consistent with both the AEO physical quantity of energy and prices. The dataset for is then typically aggregated across all states to create a single energy-economic social accounting matrix for the United States.

The MRN model is formulated as a mixed complementary problem (MCP) using the Mathematical Programming Subsystem for General Equilibrium (MPSGE) software (Rutherford 1995) and solved using the PATH solver within the Generalized Algebraic Modeling System (GAMS) (Brooke, Kendrick, Meeraus, and Raman, 2003).[12] The model is calibrated to the MRN dataset and is solved in five-year intervals to 2050, with 2010 as the first year with calculated model results.

1.2.4. Modeling Carbon Abatement Policy Instruments in MRN

Fossil fuels are consumed by all sectors in the economy - production, households, and government. To incorporate carbon emissions in the model, a constructed emissions permit is tracked for three fossil fuel inputs: coal, natural gas, and refined petroleum. The MRN model tracks emissions from fossil fuel use by all sectors and agents at all times in the model. Careful tracking of carbon use by fossil fuel and by sector in the model is necessary because the level of carbon emissions is used as a carbon policy instrument for abatement policies. Carbon abatement policies are represented as either a fixed cap on the amount of emissions

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[11] Households do not face policy uncertainty. The policies that are chosen are well-defined and assumed to be known in advance.

[12] Thomas F. Rutherford is the creator of MPSGE and also a principal developer of MRN.

that are permitted or a tax on emissions. The cap or tax on emissions can be applied to a particular sector or to the economy as a whole.

Along the BAU case, demand for allowances equals emissions. Since the allowances are not scarce the permit price is zero in the BAU case (by definition). Under a carbon abatement policy, however, the number of available allowances is constrained and hence creates a market for allowances. Firms that are able to hold their emissions below the allowable limits are in the position to sell their excess allowances at the market price, while those firms that (as a result of higher marginal cost of abatement) exceed their allowable emissions will have to either buy allowances from the market or switch to less carbon-intensive generation technologies, whichever is cheaper. A key outcome of trading is that carbon emissions are abated at the least cost to the economy as a whole.

A simple example illustrates this point. Assume that there are two firms (Firm-A and Firm-B) in an economy where each firm emits 100 tons of emissions. Firm-A is assumed to be equipped with an efficient technology and is able to cut emissions at (a constant) $5 per ton while Firm-B's (constant) marginal cost of reducing a ton of emissions is $10. The government asks each to reduce 10 tons of emissions so that the government achieves its target of reducing 20 tons of emissions for the economy. If these two firms decide to their cut emissions individually, then the cost to Firm-A and Firm-B would be $50 and $100 respectively, and the total cost to the economy would be $150. However, since Firm-A has a much lower marginal cost of reduction than Firm-B it would be better for Firm-A to take the burden of cutting all of the emissions and Firm-B to buy the allowances from Firm-A at any price between $5 and $10 per ton. For example, Firm-B would be better off paying Firm-A $7.50 per ton than abating at $10 per ton in this simple example, and Firm-A would profit as well. Under such a case, if Firm-A reduces its emissions by an additional 10 tons, then the cost to Firm-A is an additional $50. Firm-A then sells 10 tons of emission allowances to Firm-B at $7.50 per ton generating $75 of revenue to Firm-A. Firm-A would have been compensated for its cost of additional abatement through its permit sale to Firm-B, making a profit of $2.50 per ton or $25 in total for its additional 10 tons of abatement. Firm-B would save the difference between the $100 it would have paid in abatement costs and the $75 it paid to Firm-A instead ($25 savings). The $75 payment from Firm-B to Firm-A is a transfer, not a net cost to the economy (as previously mentioned, Firm-A incurs $50 in additional cost to abate the emissions for which Firm-B needs to purchase allowances). The net cost to the economy after trading is just $100 ($5 per ton times 20 tons of abatement by Firm-A) rather than $150 per ton ($5 per ton times 10 tons for Firm-A's abatement plus $10 per ton times 10 tons for Firm-B's abatement). Thus, the reduction of 20 tons of emissions is achieved at the least net cost to the economy, with a saving of $50 compared to the total cost that would have been incurred without trading.

1.2.5. Important Drivers of the MRN Model

General equilibrium model results, in general, are driven by the representation of taxes, elasticity assumptions, value shares of inputs, BAU energy prices, and growth rate assumptions. Correct tax representation and parametric values of elasticities are key assumptions that drive the general equilibrium results. Input value shares are based on established social accounting matrices and in general the results are robust to changes in these input value shares; therefore, input value shares are a less important driver. The MRN model incorporates detailed tax representation for the value-added components (labor and capital). The model uses marginal and average tax rates on labor and capital at the State and Federal level, which are important for public finance policy analysis in MRN. The application of tax regimes in MRN closely resembles actual tax implementation at the State and Federal levels. Carbon policy impacts depend on real-world aspects of regional economic systems and global trade that are incorporated in the benchmark data and projections used to define the BAU case, and also on key parameters that describe how supply, demand, and trade flows respond to the effects of policy changes. The key parameters that determine these impacts are end-use demand elasticities for energy and other goods, elasticities of substitution between different forms of energy, energy supply elasticities, and Armington trade elasticities.

The parametric values of the elasticity of substitution (constant elasticity of substitution and constant elasticity of transformation) are exogenously set in the MRN model (i.e., they are model inputs). These values are drawn from secondary sources or based on past econometric studies. The elasticity values determine the cost of tradeoffs between inputs under a policy and hence will determine the cost of the policy. Carbon abatement policy will have a direct impact on increasing the price of carbon-intensive inputs to production and also on the prices of consumption goods and services. If the production technology is such that it allows for easy substitution away from carbon-intensive inputs then there will be less of an impact as a result of carbon abatement policy. However, for energy-intensive industries, energy composes a large share of the input to production, and hence there will be less of an opportunity to substitute away from carbon-intensive inputs (fuels). The producer will either decrease inputs of carbon-based fuel or move to lower-carbon based fuels. This will result in an increase in the cost of production (compared to BAU) but is optimized with respect to post-policy prices. The price of energy-intensive goods will rise resulting in an adverse impact on the welfare of the consumer. Hence, the cost of production or consumption of carbon-intensive goods will rise and will ultimately have an adverse impact on the economy.

If the domestically produced energy-intensive good undergoes a price change relative to the imported energy–intensive good, the terms of trade between trading partners changes. Terms of trade compare the price of a region’s exports to the price of its imports. An improvement in the terms of trade means that the prices of exports rise relative to the prices of imports, so that a region with improving terms of trade obtains a greater quantity of imports for each dollar’s worth of exports. The Armington elasticity between a domestic and imported good determines how much of an imported good can be substituted at the expense of a domestically produced good. More substitution means that domestic production decreases while the exporting region's production increases, resulting in an increase in the exporting region's carbon emissions. Production is shifted from one region to another and so are carbon emissions. The Armington elasticity implicitly determines the level of carbon leakage to other regions in the presence of a policy that constrains carbon emissions.

1.2.6. Representation of Energy Efficiency Improvements

Autonomous energy efficiency improvement (AEEI) is built into the model's BAU case, that is, the number of MWh required to produce each unit of GDP declines over time in a manner that is a plausible extension of historical trends. AEEI includes both structural changes in the economy (i.e., the shift to a more service-oriented economy) and technology changes (i.e., increased penetration of energy-efficient technologies).

Demand-side energy efficiency is captured in the parameters of the model's production functions, including the energy sectors, the non-energy sectors, and the household sector. When electricity prices get higher (as under a carbon cap), more capital and labor (and possibly materials) are substituted for energy in the production of each unit of output. That is, production becomes less energy-intensive relative to the BAU case. An analogous shift occurs within households so that a unit of energy service (e.g., a particular number of lumens of light received, or the annual service of a refrigerator) require less energy because of the purchase and operation of more capital-intensive (but more energy-efficient) appliances. Households may also simply reduce their demand for energy services in response higher prices. Thus, household demand-response involves both increased adoption of energy-efficient technologies and behavioral changes that result in lower overall (direct) consumption of energy services. Because MRN is a general equilibrium model, final demand for products that contain embodied energy decrease (as the prices of products containing embodied energy rise under carbon cap) – this indirectly lowers energy demand in the model.

The model's demand response implies an elasticity of about -0.2 in the short-run, but approximately -0.6 in the long-run (e.g., after 5-10 years of continuously higher energy prices). The long-run elasticity indicates more demand response than utility planners often assume, but that is precisely because this is a long-run measure – in the long-run the capital stock of the economy becomes more energy-efficient in response to higher energy prices.

The MRN-NEEM model is not an engineering model; therefore, the model's results do not indicate specific, nameable energy-efficient technologies that were adopted more quickly under carbon policy versus the BAU case. An engineering-based model of the demand side would identify these particular technologies because they would be completely specified as inputs. As a consequence, an engineering model would progressively step through available energy-efficient technologies (in order of increasing cost-effectiveness) as energy prices rise, potentially exhausting all such known technologies under more stringent carbon caps. Of course, a modeler using an engineering model can avoid the problem of exhausting known energy-efficient technologies by defining unknown technologies in the model that embody advanced energy-efficiency. In contrast, the MRN-NEEM model captures advanced energy-efficiency by its very nature because the possibilities for substituting capital (and labor and materials) for energy are never exhausted as energy prices rise in response to carbon policy. Again, the ease with which these substitutions occur is captured in the parameters of the model's production functions.

Since consumption of energy services and energy-containing products decline in response to carbon caps, economic welfare is reduced. The drop in welfare is somewhat offset by a shift to consumption of other goods, but the price-induced shift results in lower net welfare (as the optimal consumption bundle is altered). Similarly, welfare also is reduced because both energy and energy-containing products become more expensive under a carbon policy. In terms of net welfare, it does not matter if these increased costs are borne solely by households or if they are shared among households, appliance manufacturers, and utilities. The MRN-NEEM model does not capture the distribution of welfare impacts across these sectors.

1.3. NEEM ELECTRICITY MODEL

1.3.1. Overview of NEEM

CRA's stand-alone North American Electricity and Environment Model ("NEEM") is a linear programming model that simulates a competitive electricity market for the continental United States. NEEM minimizes the present value of incremental costs to the electric sector while meeting electricity demand and complying with relevant environmental limits. NEEM was designed specifically to be able to simultaneously model least-cost compliance with all state, regional and national, seasonal and annual emissions caps for SO_2, NO_X, Hg and CO_2. The least-cost outcome is the expected result in a competitive wholesale electricity market. As part of the cost minimization solution, NEEM produces forecasts of short-term and long-term decisions such as coal choices, investments in pollution control equipment and new capacity additions in a manner that minimizes the total costs to the electrical sector.

The model employs detailed unit-level information on all of the generating units in the U.S. and large portions of Canada. All coal units are represented individually in the model, and other units are aggregated. NEEM models the evolution of the North American power system - taking into account demand growth, available generation, environmental technologies and environmental regulations - both present and future. The North American interconnected power system is modeled as a set of regions (generally NERC regions and NERC sub-regions, but can be specified in any level of detail required for analysis) that are connected by a network of transmission paths.

Environmental regulations affect decisions about: (1) the mix and timing of new capacity, (2) retirement of existing units, (3) the mix and timing of environmental retrofits at existing facilities, (4) fuel choice, primarily by coal units, (5) dispatch of all units, (6) maintenance scheduling for all units, and (7) the flow of power among regions. NEEM captures all of these impacts in the process of optimizing unit responses to environmental policies. For cap-and-trade policies, NEEM also determines permit banking decisions.

In order to be integrated with MRN, NEEM has been formulated as a quadratic program instead of the linear program structure used in the stand-alone model. It solves for the optimal decisions by maximizing the present value of consumer and producer surplus subject to economic, technical, and policy constraints. The economic constraint is that the supply and demand for electricity is balanced in each region. Technical constraints include operational limits, maintenance requirements, and maximum output. Policy constraints include the required reserve margin and also State and Federal environmental constraints (i.e., emission caps, efficiency standards, and RPS standards).

The total surplus is equal to the area between the demand and supply curve for electricity. NEEM employs a linear demand curve that is benchmarked to the exogenous forecast of demand and the resulting marginal cost of providing electricity to meet this demand. The electricity supply curve represents the cost of supplying electricity, which includes (1) fixed and variable operating costs for all units, (2) fuel costs, (3) capital investments in new plants and retrofits at new and existing facilities, and (4) the cost of moving power between regions (wheeling charges). NEEM also estimates wholesale power prices by region, year, and load block, and the value of an additional MW of capacity (a capacity price) for each region with a defined reserve margin.

The mathematical integration of NEEM and MRN is discussed more completely in Section 1.4.

1.3.2. Model Scope

NEEM employs a flexible modeling structure so that the model scope can change to best match the scope of the problem at hand. NEEM is a process-based model of U.S. electricity markets and portions of the Canadian system. NEEM typically divides U.S. electricity markets into 27 individual demand regions, plus four Canadian regions, interconnected by limited transmission capabilities.

The user defines the time horizon for NEEM. Because of the long life-span of generating units, capital decisions affect decisions for several years. Therefore, NEEM’s model horizon is generally 40 or 50 years. NEEM dispatches to a load duration curve. The load duration curve first breaks up hourly demand into three seasons - summer, winter, and shoulder. The summer is defined as May through September; the winter includes December, January and February; and the shoulder period includes March, April, October and November. Hourly demand within each season is then sorted from highest to lowest and placed into load blocks. The demand within any load block is then the average hourly demand of the hours within the load block. The load blocks have been created to best represent the relative peakiness of energy demand. As such there are fewer hours included in peak demand load blocks and more hours in the off-peak demand load blocks. The typical NEEM model includes 20 load blocks.

Coal units (and other units of interest) are represented in detail as these are most affected by environmental regulation. All but small coal units are modeled at a unit level. All non-coal generating units in the United States are also represented in the model, with some level of unit aggregation. In addition to coal units, NEEM represents the following generation technologies - natural gas combined cycle (CC), natural gas combustion turbine (CT), nuclear (Nuc), integrated gasification combined cycle (IGCC, also available with carbon capture/sequestration), hydroelectric (H), pumped storage hydro (PS), and a range of renewable technologies. Renewable technologies include: wind (WT), solar photovoltaic (PV), solar thermal (ST), landfill gas (LG), biomass (BM), and geothermal (GEO).

NEEM can model virtually any environmental policy concerned with emissions of SO_2, NO_x, mercury, or CO_2. NEEM tracks these four emissions. One option for compliance is retrofitting. In NEEM, coal units can add the following retrofit options to reduce emissions: flue gas desulfurization (FGD) for removal of SO_2; selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) for removal of NO_X; mercury retrofits include activated carbon injection (ACI90 and ADVACI) and ACI with a fabric filter (RPJ90); and finally IGCC units can be retrofitted to sequester most of its carbon emissions.

1.3.3. Defining the Set of Existing Units

The NEEM data file includes all existing generators in the United States (and often in selected regions of Canada). This includes coal-fired, natural gas-fired, steam oil/gas, nuclear and renewable units.

For purposes of model flexibility many of the units are aggregated together based on unit type and unit size, as well as the location of the unit. Aggregated units are given a name to indicate the type of unit and the location of the unit.

Coal Units

All existing coal units that are 200 MW or greater (based on summer capacity) are represented individually and are not included in aggregates. Generally, coal units smaller than 200 MW are aggregated within their regions.

Smaller coal units within each region are combined into one of the three aggregates. Coal grouping 1 includes units with a capacity less than 100 MW; coal grouping 2 includes units with a capacity less than or equal to 150 MW (and greater than or equal to 100 MW); coal grouping 3 includes units with capacities greater than 150 MW and less than 200 MW. The units between 150 MW and 200 MW are aggregated only to the extent that they:

- Are at the same station,
- Are of similar size,
- Have similar heat rates,
- Use the same coal type or types,
- Have the same current and planned environmental retrofit equipment installed.

Thus, the 150-200 MW coal units are aggregated such that only units that are almost indistinguishable from a modeling perspective are combined.

The above-described aggregation is performed for each region and almost all regions have three coal units that represent the aggregates defined above.

Oil- and Gas-Fired Units

Combined-cycle natural gas units are aggregated based on their year-in-service. Year-in-service is used to estimate the units' respective heat rates because the year-in-service is linked to the type of turbine likely to be used. The database includes three groupings. Those units with in-service years later than 1999 are included in the first grouping, units with in-service dates from 1990 through 1999 are included in the second grouping, while all others are included in the third grouping. Again as with the aggregation of the coal units, this aggregation is performed on a regional level.

The aggregation methodology for natural gas-fired peaking units is similar to that for combined-cycle units except there are only two groupings. Units with an in-service date greater than 1988 are classified in the first grouping for peaking plants, while all others are included in the second grouping.

Aggregation of steam oil/gas and peak oil units are both based on the units' heat rates. They are included in one of three groups based by region. Units with heat rates of 10,000 Btu/kWh or less are included in the first grouping; units with heat rates less than 13,000 Btu/kWh (but greater than 10,000 Btu/kWh) are included in the second grouping; and units with a heat rate greater than or equal to 13,000 Btu/kWh are included in the third grouping.

Other Unit Types

All other types of units (*e.g.*, nuclear, wind, *etc.*) are aggregated together into a single unit within each region – one unit for each type within each region.

1.3.4. Data Sources and Assumptions for Existing Units

Coal Fired Units

Data on the coal units comes from a number of sources. The source of the coal units operating in the United States is predominantly from EIA Form 411, while CRA also monitors newswires for coal unit retirements and checks RDI NewGen for newer coal units. Information on each unit's capacity is also from the EIA Form 411. Existing plant configuration also comes from a number of sources including the EIA Form 767, McIlvaine's database of controls, quarterly CEMS filings and monitoring of the trade press. Planned outage information is from eGADS and is based on the plant type and unit size (for coal units).

Data on NO_X unit emission rates are from third-quarter CEMS reporting. Third-quarter data is used as all three months of the quarter are part of the ozone season. As a result, reported NO_X rates from the third quarter best represent the NO_X rate when any post-combustion controls are operating.

Information on each coal unit's initial coal is based on coal deliveries to that plant in the most recent year for which data are available. This information is available through RDI's CoalDat.

Oil- and Gas-Fired Units

Important characteristics for the natural gas and oil-fired units are similar to those for the coal units. The initial set of natural gas-fired and oil-fired units is from NERC ES&D 2005. Queries of existing generators were performed for units with a primary fuel of natural gas or oil (all types of oil). Only those units that were currently operating according to ES&D were included. Planned and forced outage rates for these units are based on eGADS. NO_X emissions rates are based on typical emissions rates for these types of units.

Nuclear Units

Information on nuclear units is available from many sources including NERC ES&D and the Nuclear Energy Institute. Outage information has been set such that the capacity factor for nuclear generators is 90 percent (18.25 planned outage days and 5% forced outage rate), which is slightly below the capacity factor of the U.S. nuclear fleet over the last several years. Since nuclear generators will operate full out, the other important characteristic besides outages is capacity. Over the last several years many nuclear generators have increased their rated capacity through uprates. Many others are projected to add uprates over the next several years. NEEM includes these projected uprates based on EIA AEO information on capacity of existing nuclear generators.

Non-Hydro Renewable Units

NEEM includes information on existing renewables generation including wind, geothermal, solar, biomass, and landfill gas. The capacity in each region is also based on information from NERC ES&D 2005 and sometimes supplemented with additional sources.[13] Wind is assumed to have a maximum capacity factor of 30%. The intermittency of wind generation is simulated using a 60% forced outage rate, in addition to 36.5 days of planned outages (another 10% of the year).

Intermittent renewables are modelled as fixed hourly patterns of output per installed MW, and as having a contribution to regional capacity that is less than the installed capacity. For example, a MW of wind in a region will provide a fixed pattern of expected hourly output and, typically, 30% of the installed MW is credited towards regional capacity reserves.

Renewable Performance Standards are modelled as minimum capacity or generation requirements for renewables within a region. The user can also specify a price at which renewable credits are available in a region. The cost of meeting the RPS standards is captured in the total price for electricity.

Hydroelectric and Pumped Storage

NEEM includes information on existing hydroelectric and pumped storage resources. No new hydroelectric or pumped storage resources are available in the model. Hydroelectric generation is limited in each season based on average levels of hydroelectric generation from CRA’s GE MAPS assumptions. Pumped storage is assumed to have an efficiency of 75 percent.

1.3.5. New Units - Data Sources and Modelling

NEEM allows for the addition of a range of new generation types. These additions include both *forced new generation*, which is new generation that is already under construction, and *economic new generation*, which is the result of additions that the model determines endogenously to be needed to minimize total system costs and/or comply with reserve requirements.

NEEM currently allows the following types of new generation: natural gas combined cycle (CC), natural gas combustion turbine (CT), pulverized coal (Coal), nuclear (Nuc), integrated gasification combined cycle (IGCC, also available with carbon capture/sequestration, IGCC-Seq), and a range of renewable technologies. Renewable technologies include: wind (WT),

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[13] Capacity for Geothermal resources in California is from the California Energy Commission (http://www.energy.ca.gov/database/POWER_PLANTS.XLS)

solar photovoltaic (PV), solar thermal (ST), landfill gas (LG), biomass (BM), and geothermal (GEO).

In CRA generic MRN-NEEM runs, costs and characteristics for these technologies are based primarily upon recent EIA AEO documentation, although CRA uses other information sources to refine EIA's estimates. Capital costs are calculated based on EIA's Total Overnight Cost. Interest during construction is then added to these figures. For individual clients and individual MRN-NEEM runs, CRA requests that a set of technology cost and performance characteristics be provided.

AEO data on coal technologies are assumed to be based on units using eastern bituminous coals. NEEM, however, needs data for pulverized coal plants and IGCC plants using both eastern bituminous and western sub-bituminous coals. A recent EPA report on coal technologies was used to adjust the capital cost and heat rates reported in AEO for plants using western sub-bituminous coals.[14]

The Electric Power Research Institute estimates that plant capital costs had increased about 12% in real dollar terms during 2004 and 2006.[15] Based on this, AEO capital costs for all but simple- and combined-cycle natural gas plants were adjusted. AEO capital costs for simple- and combined-cycle natural gas plants appear to have been adjusted to reflect current capital costs.

The variable operating and maintenance costs for sub-bituminous pulverized coal units are significantly lower than for bituminous units since the lower sulfur content of sub-bituminous coals requires less limestone feedstock. An EPA report was used to estimate the change in variable costs when using sub-bituminous coal at a pulverized coal unit.[16]

AEO capital costs do not include transmission, rail spur, or natural gas pipeline costs. AEO projections only include items inside the plant "fence." CRA provided estimates for these additional items.

To avoid large quantities of installations of certain generation types in a single year, NEEM also includes limits on how much of different generation types can be built in different years. For example, while the first nuclear power plant might become operational in 2015, it is

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[14] Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies, Final Report, U.S. Environmental Protection Agency, July 2006.

[15] Electric Power Research Institute Technical Assistance Guide, December 2005.

[16] Standalone Documentation for EPA Base Case 2004 (V.2.1.9) Using the Integrated Planning Model, United States Environmental Protection Agency, Office of Air and Radiation (6204J), EPA 430-R-05-011, September 2005.

unlikely that there will be 20 new plants in that year. Therefore, a user can enter cumulative limits on the quantities that can be built to reflect a more likely (maximum) penetration schedule. NEEM determines based on economics whether or not nuclear penetration would be slower than the user-defined trajectory.

CRA tailors the technology cost and performance characteristics for each MRN-NEEM run based on information provided by its clients. Likewise, the technology penetration limits also vary from run to run.

1.3.6. Transmission

NEEM's regions have been created to address primary transmission limitations and constraints. Within a NEEM region there are no transmission limitations. Inter-regional transmission limitations are represented based on NERC data on transfer limits. Limits are represented in both directions (*e.g.*, from Region A to Region B and from Region B to Region A). NEEM has the flexibility to allow for changes in transmission capacity over time. These changes are specified exogenously (i.e., are not determined within the model).

NEEM also allows a user to specify a cost for transmission between any NEEM regions and also to specify the percentage of line losses from one region to another. These inputs can change over model years.

1.3.7. Environmental Compliance Technology Inputs for Existing Generators

The model data include existing equipment for each unit, which determine the starting emission rates for each pollutant for each unit. Existing equipment that is tracked includes scrubbers for SO_2 control, selective catalytic reduction units (SCRs) for NO_X control, selective non-catalytic reduction units (SNCRs) for NO_X control, electrostatic precipitators (ESPs) for control of particulates, and fabric filters for control of particulates. This existing equipment also determines the level of mercury "co-benefits" that a unit will achieve (i.e., mercury emissions are controlled to some extent in controlling other emissions).

For each NO_x-emitting generator, the input data includes a NO_x emission rate,[17] which is automatically adjusted if retrofits that reduce NO_x are added to the unit. The input data do not include explicit SO_2 or mercury emission rates for each coal plant, since these are a strong function of both the type of coal burned and the existing control equipment. Consequently, these emissions are calculated taking into account the fuel and existing equipment for a unit.

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[17] The NOx emissions rate is assumed to be unaffected by coal type.

1.3.8. Environmental Retrofit Modelling

The NEEM data file includes environmental retrofits for existing coal-fired units to reduce emissions of SO_2, NO_X, mercury, and CO_2. Coal-fired units can also switch coal types by expending the necessary capital to retrofit the plant.

Retrofit options currently include: flue gas desulphurization (FGD) for removal of SO_2, selective catalytic reduction (SCR) for removal of NO_X, and selective non-catalytic reduction (SNCR) for removal of NO_X. Mercury retrofits include activated carbon injection (ACI90 and ADVACI) and ACI with a fabric filter (RPJ90). There is also a carbon capture and sequestration (SEQ) retrofit to reduce CO_2 emissions, although this technology is not currently available and is not likely to be available for at least ten years. The costs and performance parameters for these technologies were developed from EPA and EPRI sources.

Retrofit options are provided for each coal unit, based on currently installed environmental retrofit equipment (which is tracked by NEEM). NEEM can install any combination of retrofit equipment as needed in future years. For example, a unit can install an FGD in 2010, an SCR in 2015, and then activated carbon injection in 2018. Planned future retrofits are modeled as equipment that NEEM will install in the planned year.

Mercury co-benefits are modeled as a function of particulate control equipment installed, rank of coal, SO_2 equipment installed (e.g., type of FGD), and NO_x equipment installed (e.g., SCR).

The model selects retrofit installations based upon economics, with the exception of planned retrofits. Planned retrofits include publicly announced retrofits that CRA has identified through the trade press and through a subscription to McIlvaine. In addition, retrofits believed to be required for units to comply with the Clean Air Visibility Rule (CAVR) are also forced into the model in 2014. Forced retrofits are added on the Existing Unit Data worksheet.

The capital cost information for retrofits was initially based on EPA estimates included in documentation of the IPM model.[18] However, CRA believes that EPA's estimates for FGD and SCR are outdated and are no longer representative of likely costs; therefore, these costs have been updated using a variety of sources. Capital costs for SNCR are still based on EPA estimates. The cost curves applied in NEEM are also still based upon EPA cost curves. Fixed O&M and variable O&M are based on EPA assumptions as well. Cost information for ACI and ACI plus fabric filter are based on calculations performed by CRA of injection rates and estimated sorbent and disposal costs from testing of activated carbon injection at a number of sites. Costs for the ADVACI retrofit, which utilizes a halogenated sorbent, are

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[18] EPA's model documentation of retrofit costs is available at http://www.epa.gov/airmarkets/epa-ipm/bc5emission.pdf.

preliminary and should be confirmed prior to including this retrofit in any analyses. Thought must also be given prior to using the SEQ retrofit (carbon sequestration) with respect to both costs and presumed timing of availability of this retrofit (this is a key driver within the model when the SEQ retrofit is allowed).

1.3.9. Coal Supply

Coal supply is represented by a set of 21 different coals that represent different regional sources, ranks, sulfur, and mercury content. Each coal that can be delivered to and utilized at a unit has transportation cost from mine mouth to plant gate. Essentially, because transportation costs to each plant vary, there are 21 coal supply curves for each coal plant. NEEM's (partial) equilibrium solution provides a set of mine-mouth prices for each coal type and delivered prices for feasible coals to each plant.

The coal supply curves are based on a model of projected production capabilities at mines throughout the United States created by Norwest. Norwest also estimated the price per ton of coal production at each mine. Using this information, along with information from the Energy Information Administration (EIA), input from clients and input from Jamie Heller (Hellerworx, Inc.), CRA created supply curves based on tranches. The number of tranches and the quantity of tons within each tranche varies by coal type and is a function of mine capabilities.

CRA has created a set of transportation matrices that match coal types to plants. There are four possible modes of transportation: barge, truck, mixed mode (*i.e.*, transload from rail to barge) and rail. The matrices are then populated based on information in RDI CoalDat. Coal plants that do not have a viable delivery option via one of the modes of transportation have a blank entry in the matrix. If there is a delivery option, then the delivery cost is calculated based on one of the following: 1) actual transport cost for the plant, 2) weighted-average transport cost for all plants in the region for the particular coal/mode of transportation combination, or 3) CRA estimate of transport cost based on a plant's distance from the production basin and the $/ton-mile for that coal.

1.3.10. Modeling Environmental Policies

One of the primary functions of NEEM is to determine compliance strategies with different environmental policies. NEEM has the flexibility to model many different types of environmental policies and in many forms.

NEEM can model environmental limitations on SO_2, NO_X, mercury, and CO_2. The forms of these constraints can take on a number of different forms including caps, emissions prices (taxes on emissions), maximum required emission rates, and required emissions reductions (from the uncontrolled inlet stream). In addition, these constraints or taxes can be applied nationally, regionally, by state or even on particular units.

NEEM includes the following emissions constraints as standard: the SIP Call for ozone season NO_X reductions (present through 2008), Title IV and CAIR SO_2 (Title IV merges with CAIR SO_2 in 2010) for SO_2 reductions, the Clean Air Interstate Rule (CAIR) NO_X Annual (cap begins in 2009) and seasonal (ozone season cap begins in 2009), the Clean Air Mercury Rule (CAMR) for mercury reductions (begins in 2010), and the Clean Air Visibility Rule (CAVR), which begins in 2014.

An important part of existing cap-and-trade regulations is the quantity of any banked allowances. Banked allowances are earned through early reductions below a capped level and can generally be applied in later years when a cap might be lowered. The existing SO_2 bank is calculated annually based on the previous year's SO_2 bank and the difference between SO_2 allowances and emissions in the most recent year.

The opportunity to use offsets to meet emission constraints can also be important. Offsets are emission reductions that are made outside the U.S. electric sector (potentially internationally), but can be purchased by generation owners within the electric sector. The most common form of offsets is CO_2 offsets that might be available under a 4-pollutant bill.

1.3.11. Forecasts

Demand growth (average and peak demand)

Regional, annual energy demands and regional peak demands are based on information provided by NERC ES&D 2005. These regions do not correspond perfectly with NEEM regions so some allocations and partitions are made to the ES&D data. Further, ES&D data only goes out ten years, after which the average regional growth rate over the last five years of projections is applied to both energy and peak demands for our national forecast. In evaluating a particular system or region, different growth rates for energy and peak demand can be assumed.

Oil and Gas prices

The NEEM model relies on external forecasts for oil and gas prices. Natural gas prices are provided on a seasonal basis for each year for each natural gas-fired unit in the model. There are three seasonal prices - summer, winter and shoulder - that correspond with the three demand seasons. The natural gas prices are based on NYMEX Henry Hub futures and EIA's AEO projections of the wellhead price. These prices are seasonally adjusted based on historical monthly prices. The prices are then converted into regional delivered prices based on historical basis differentials.

Distillate oil prices are calculated in a similar manner to the natural gas prices. They are primarily based upon NYMEX Light Sweet Crude Futures and EIA's AEO projections of the world oil price. Oil prices in NEEM are only included as annual prices.

Other Forecasts

- Coal price and supply forecasts are determined by the coal supply curves described above.
- Introduction dates and (maximum) penetration rates of new technologies are inputs to NEEM.

1.3.12. Methodology for Using NEEM to Analyze Carbon (or other Environmental) Policies

To analyze an environmental policy, NEEM must first be solved for a BAU case in which the policy is not in force. In addition, the BAU case must be consistent in that the exogenously specified demand (i.e., the demand input by the user) matches the demand expected under the set of policies and market conditions assumed in BAU. *From the BAU-case solution, the equilibrium prices that are associated with exogenously specified demands are extracted. These prices along with the exogenously specified demand comprise the benchmark price and quantity points for the electricity demand curve.* These electricity demand curves are defined for each region modeled.

To solve for the carbon policy, or scenario case, the environmental policy of interest is applied, and the NEEM model is resolved. In the scenario case, electricity demand is no longer fixed and therefore demand is responsive to the environmental policy of interest. The model solves for the optimal set of decisions under the policy.

1.4. MRN-NEEM INTEGRATION METHODOLOGY

The integration of the two large models discussed above, MRN (top-down) and NEEM (bottom-up), poses multiple challenges. Thus, the explanation in this section of CRA's approach to these challenges is somewhat technical.

The model integration is computationally challenging because of its dimensionality and caution must be applied to ensure consistency between the models that are structurally quite different. Different approaches have been proposed in the literature attempting to couple these two types of models including (1) a "soft-link", (2) building a truly integrated model, or (3) employing an iterative method to incorporate general equilibrium effects within the context of technology-oriented bottom-up models. CRA uses a decomposition technique that closely follows the third approach. The proposed method by Bohringer-Rutherford (Bohringer-Rutherford, 2005) overcomes complexity and dimensionality restrictions and converges rapidly.[19] The method utilizes an iterative process where the MRN and NEEM models are solved in succession to reconcile the equilibrium prices and quantities between the two models. The solution procedure, in general, involves an iterative solution of MRN (top-down) given the quantities from NEEM (bottom-up) followed by another solution of NEEM based on a locally calibrated set of linear demand functions for the energy sector outputs. The two models are solved independently using different solution techniques but linked through iterative solutions points. The MRN model is solved using the mixed complementary method while the underlying linear program of the NEEM model is converted to a quadratic program formulation and solved as a partial equilibrium model.[20]

The key to the integration approach is recasting the NEEM linear program with fixed demand to a partial equilibrium model with a demand function. A cost-minimization linear program can be converted to a quadratic programming problem that maximizes total surplus assuming a linear demand function calibrated locally.

The sequence of the iterative process and the partial equilibrium modeling is illustrated in the figures below. In

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[19] This section is largely drawn from the Bohringer, C. and Thomas F. Rutherford, 2005, “Combining Top-Down and Bottom-up in Energy Policy Analysis: A Decomposition Approach,” Centre for European Research (ZEW), Mannheim, Germany. The authors demonstrate that a single integrated model of a top-down sub-model and a bottom-up sub-model can be effectively formulated as a mixed complementary problem (MCP) and solved. Despite the logical appeal of an integrated approach, an integrated model of MRN and NEEM would be highly complex and computationally challenging due to the dimensionality of the model. Mathematically, MCP formulation would involve the primal and dual formulation of the problem that would only add additional dimensionality.

[20] One might be tempted to perform an iterative solution between the general equilibrium model and the cost minimizing linear program (LP), however, this process will likely fail because the LP formulation does not have the ability to take into account demand responses to changes in prices.

Figure 3, an initial guess is made for solution point ***a*** on the demand curve **D**. A linear demand function is constructed locally around this point assuming an arc elasticity of ε. The downward sloping linear demand function is as follows:

$$p(e)=\bar{p}\left[1-\frac{\left(e-\bar{e}\right)}{\varepsilon\bar{e}}\right]$$

where $\left(\bar{p},\bar{e}\right)$ are the initial reference price and quantity pair at point ***a***. This linear demand function is handed to NEEM where it intersects the piecewise linear supply schedule, **S**. In Figure 4, the new equilibrium point solution point $\left(c1,Q1\right)$ is achieved if the areas under the linear demand curve and area above the supply schedule is maximized. This area represents total surplus and is shown as the red shaded area in Figure 4. The linear demand curve and the supply schedule form the bottom-up partial equilibrium model. The area under the linear demand or the integrated market demand is a quadratic function and represented as:

$$\int p(e)de=\bar{p}e_i\left[1+\frac{\left(2\bar{e}-e\right)}{2\varepsilon\bar{e}}\right]$$

Without loss of generality, an aggregate multi-commodity bottom-up model may then be solved as a quadratic programming problem of the form:

$$\bar{p}^{T}\left(e-x\right)+\frac{1}{2}\sum_{i}\frac{\left(\bar{p}_{i}e_{i}\right)}{\varepsilon_{i}\bar{e}_{i}}\left(e_{i}-2\bar{e}_{i}\right)$$

The quadratic program that is solved as the bottom-up model in the integrated model takes the following canonical form:

$$\text{Max} \quad \bar{p}^{T}e+\frac{1}{2}\sum_{i}\frac{\left(\bar{p}_{i}e_{i}\right)}{\varepsilon_{i}\bar{e}_{i}}\left(e_{i}-2\bar{e}_{i}\right)-Z$$

Subject to

$$Ax+Bz\geq Ce$$

$$e,x\geq 0,\ l\leq z\leq u$$

where **p** denotes prices, ***e*** is energy outputs of the energy system, ***x*** is inputs to the energy system, and ***Z*** is the cost-minimizing LP objective function of the bottom-up linear program. The solution of this energy sub-problem will yield energy supply of ***Q1*** at a marginal cost of ***c1*** (see Figure 4).

This supply quantity is handed back to MRN as a reference quantity for calibration of the demand. The resulting solution from MRN is (***P1***,***Q1***), see Figure 5. Then as before, a linear demand is generated through the point ***b*** and handed back to NEEM to be solved as a partial equilibrium model once again. This process is repeated until the quantities solved for in NEEM and the prices solved for in MRN converge to a consistent, equilibrium price-quantity pair of (**P***,**Q***) as shown in Figure 6.

In the figures' depiction so far, general equilibrium has not been addressed and hence cross-market price effects have not yet shifted the demand. This is not the case in a multi-commodity economy where general equilibrium effects and cross-market price responses induce changes in the demand from iteration to iteration. The iterative process with shifting demand is illustrated in Figure 7. In simple terms, the MRN-NEEM convergence process seeks the same equilibrium in both the MRN and NEEM models and demand for all products (not just energy) change in the MRN sub-model as carbon policy price-effects ripple through the economy. These effects are larger for energy-intensive goods and services.

Figure 3. Graphical exposition of the decomposition method

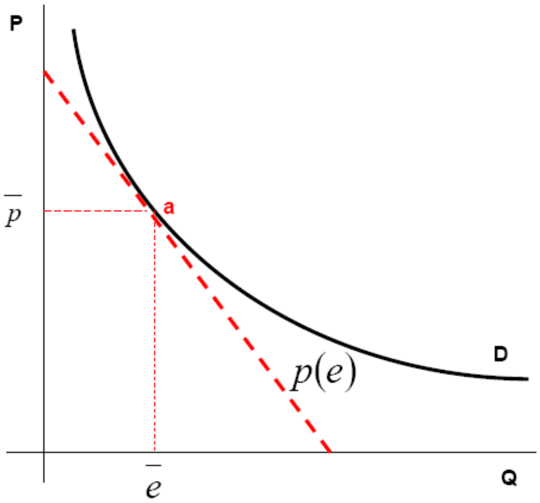


Figure 4: Quadratic formulation

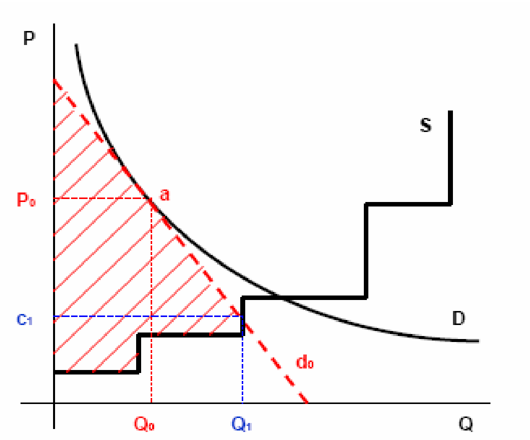


Figure 5: Step-2 Iterative process

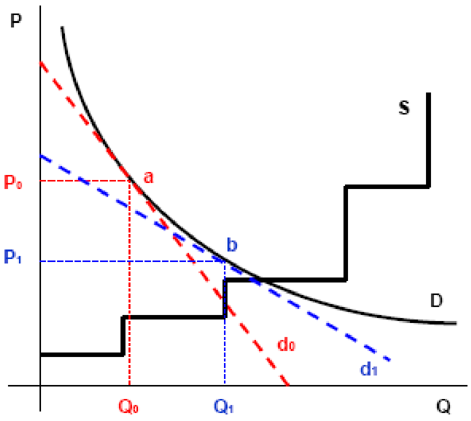


Figure 6: Step-3 Iterative process

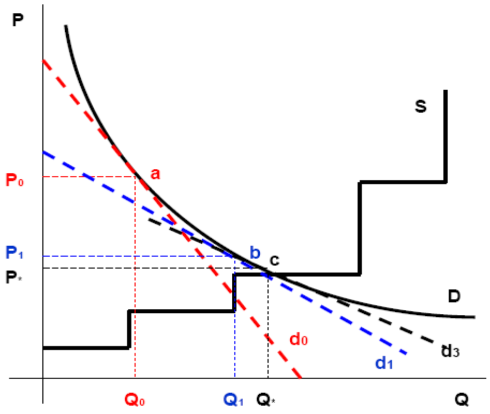
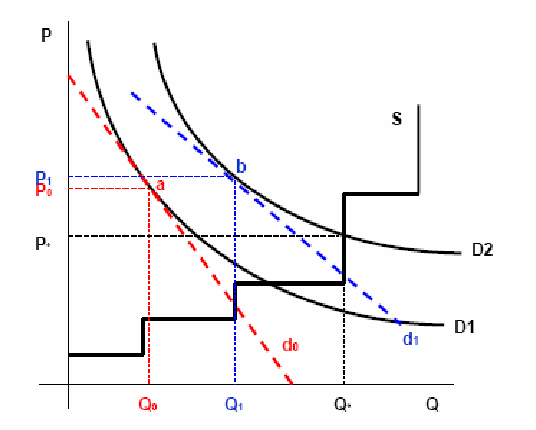


Figure 7: Step-4 Iterative process



In the current MRN-NEEM integrated model, as discussed in Section 1.2.3, MRN accounts for all sectors except for the electric utility and coal supply sectors. The level of utility demand for gas, the supply of electricity, and the demand for electricity are exogenous to MRN (these are provided by the NEEM model). The MRN model is then solved for a new equilibrium and provides NEEM with the supply and price of gas, a new demand level and price of electricity, a non-utility demand for coal, and coal prices. If emissions trading between utility and non-utility sectors is assumed, then MRN further provides the non-utility carbon allowance demand and price. In a nutshell, MRN supplies functions for electricity demand, non-utility coal demand, non-utility carbon allowance demand, and the supply of gas. NEEM accepts MRN's outputs as inputs and vice-versa, as shown in Figure 8 and Figure 9.

Figure 8: MRN Data Inputs and Outputs in the MRN-NEEM Iterative Process

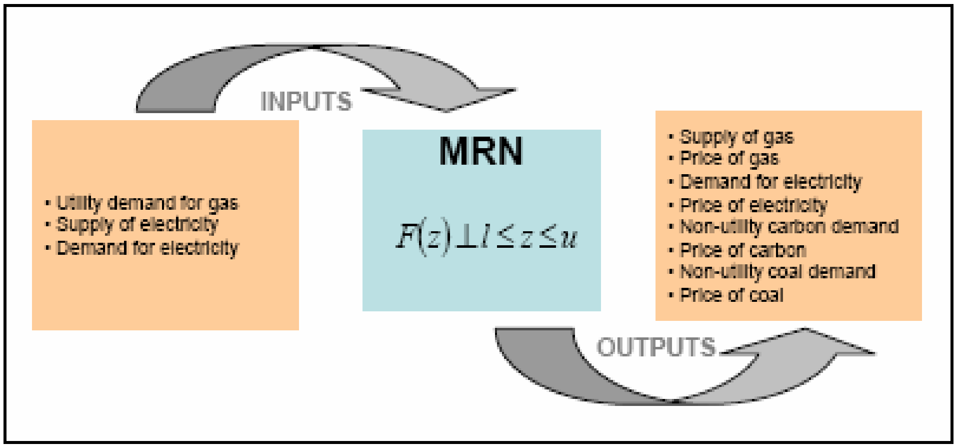


Figure 9: NEEM Data Inputs and Outputs in the MRN-NEEM Iterative Process