HAIKU DOCUMENTATION: RFF'S ELECTRICITY MARKET MODEL VERSION 2.0

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Haiku Documentation:

RFF's Electricity Market Model

version 2.0

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AN RFF REPORT

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Abstract

RFF's Haiku model is a simulation of regional electricity markets and interregional electricity trade in the continental United States. The model accounts for capacity planning, investment, and retirement over a multi-year horizon and for system operation over seasons of the year and times of day. Electricity demand is represented by price-sensitive demand schedules by customer class, and changes in demand can be implemented through investments in energy efficiency, time of day pricing, and other regulatory changes. The model identifies least-cost compliance strategies for compliance with various types of regulations of sulfur dioxide, nitrogen oxide, carbon dioxide, and mercury emisisons. Market structure is represented by cost-of-service (average cost) pricing and market-based (marginal cost) pricing in various regions.

This documentation provides an overview of model capabilities and examples of how it has been used in many previous reports and scholarly studies. The documentation provides additional detail where necessary to explain economic or regulatory concepts or modeling strategies.

Key Words: electricity, air pollution, regulation, energy

JEL Classification Numbers: Q40, L94

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1. Introduction

The Haiku model is a simulation of regional electricity markets and interregional electricity trade in the continental United States that accounts for regulations to control emissions of nitrogen oxide (NO_x), sulfur dioxide (SO_2), carbon dioxide (CO_2), and mercury from the electricity sector. The model can project market equilibrium in each of 21 regions of the lower 48 states through the year 2030 during three seasons of the year and four time blocks within each season. Electricity demand is characterized by price responsive functions for each region and time period for three sectors of the economy: residential, commercial, and industrial. Electricity supply is characterized for each region and time period by a set of fully integrated modules that determine generation capacity investment and retirement, system operation including interregional power trading, prices and production in fuel markets, and compliance strategies for emissions regulations including investment in pollution abatement technologies. Generation capacity is classified in model plants that are distinguished by geographic region and a set of salient technology characteristics including fuel type, vintage, and generator technology. Haiku has versatility in simulating pollution abatement policies as well as emerging electricity market structures and calculates relative measures of economic welfare. The model runs on a desktop computer and serves as a laboratory for sophisticated first-order policy analysis for the electricity industry in the United States. This document describes the model.

Haiku utilizes two software platforms. The manipulation of raw data is performed using Stata. The model itself works on a pair of software packages developed by Lumina Decision Systems, Inc. The code is written and the results are observed using Analytica. The Analytica code is solved by the Analytica Decision Engine, which is called by a Visual Basic program. In Analytica, each variable appears as a node within an influence diagram. Hence, the screen views of the model itself allow those who are unfamiliar with Analytica code to understand the basic relationships that define the model.

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[*] The development of Haiku has benefited from the contributions of many persons. The contributors are Ranjit Bharvirkar, Dallas Burtraw, David Evans, Danny Kahn, David Lankton, Erica Myers, Karen Palmer, and Anthony Paul.

The subsequent sections of this chapter provide an overview of the modeling approach and a description of the most important features of the model. Chapter 2 is an outline of the institutions and policy alternatives that Haiku is designed to simulate and Chapter 3 is a detailed description of the model's components.

Overview of Modeling Approach

Haiku is designed as a laboratory for exploring the economics of public policies within the electricity sector. Particular emphasis is placed on two types of policies, those designed to reduce airborne emissions from electricity generators and to reform electricity markets. The model is equipped with the detail necessary to address these issues and deliberately omits details of the electricity sector that do not bear directly on these issues. Since many policies of these two types have national scope, Haiku also has national scope. A detailed bottom-up type engineering model of national scope that simulates each individual generator and power line at all instants in time is a computational impossibility. The reduced form approach adopted in Haiku aggregates generators with similar technological characteristics into model plants that are representative of the generators in 21 regions of the continental United States. The hours of a year with similar load (electricity demand) characteristics are aggregated into time blocks. Each model plant is parameterized by measures of variable cost, fixed cost including capital cost, operating efficiency, and compatibility with a suite of post-combustion controls for conventional air pollutants. Electricity demand is projected using a top-down econometric model to represent consumer behavior in three customer classes: residential, commercial, and industrial. Haiku is equipped to model the traditional cost-of-service method of electricity pricing as well as competitive market pricing.

The reduced form mode of simulating the electricity sector that is employed by Haiku is imperfect. There are myriad details of generator and transmission system operation, consumer behavior, local laws and regulations, and market rules that Haiku does not explicitly capture. Furthermore, the model is populated with volumes of data, some of which are approximated, and though they are acquired from reputable and documented sources, they are inherently imperfect. Two techniques are used to overcome these problems: calibration and delta analysis. The model is calibrated to match a subset of the electricity sector outcomes published annually by the Energy Information Administration (EIA) in the Annual Energy Outlook (AEO) and the suite of documents that accompany it. This technique captures the details, in reduced form, that are otherwise ignored by the model in parameters called calibrators. The calibrators bear directly on a small subset of model outputs, but the majority of outputs are outside the domain of calibration and thus the potential exists for results that do not match reasonable real world outcomes. To circumvent such problems, the operational mode of Haiku analysis is delta analysis, which focuses on the comparison of a baseline scenario with alternative scenarios. This method renders erroneous point estimates irrelevant except to the extent that the calibrators are correlated with alternatives of scenario specification.

Haiku is equipped for scenario analysis with a wide array of inputs that are separate from the core data on which the model operates. These inputs allow the user to implement the delta analysis method by defining a baseline scenario and a set of alternative scenarios, all of which are solved separately. About half of the user inputs are related to policies designed to reduce airborne emissions from the electricity sector. The other half relate to specifications of electricity market institutions and assumptions about technology and the macro economy. Figure 1 is a schematic of the flow of information around Haiku. The user defines all parameters listed in the upper left box. Haiku then reads these parameters in addition to the core dataset to produce the model outputs.

Haiku is a deterministic and forward-looking model that finds equilibrium in electricity markets over any number of simulation years between the data initialization year[1] and the year 2030. Often the model is run for five simulation years that span 2010 to 2030 in 5-year increments. Estimates for intervening years can be derived by interpolating results between the simulation years. Because power plants are long-lived investments, and capacity investment and retirement decisions must account for revenue and cost streams over a long time horizon, the model finds simultaneous equilibria for each simulation year assuming perfect foresight about the future. Perfect foresight is a strong assumption that cannot be relaxed in the Haiku modeling structure; as a result, the model is deterministic. This limitation is addressed through either sensitivity analysis in which alternative deterministic solutions are found for varying input assumptions or through approximation methods using finite differences to estimate the nonlinear behavior of the model over a set of random variables.

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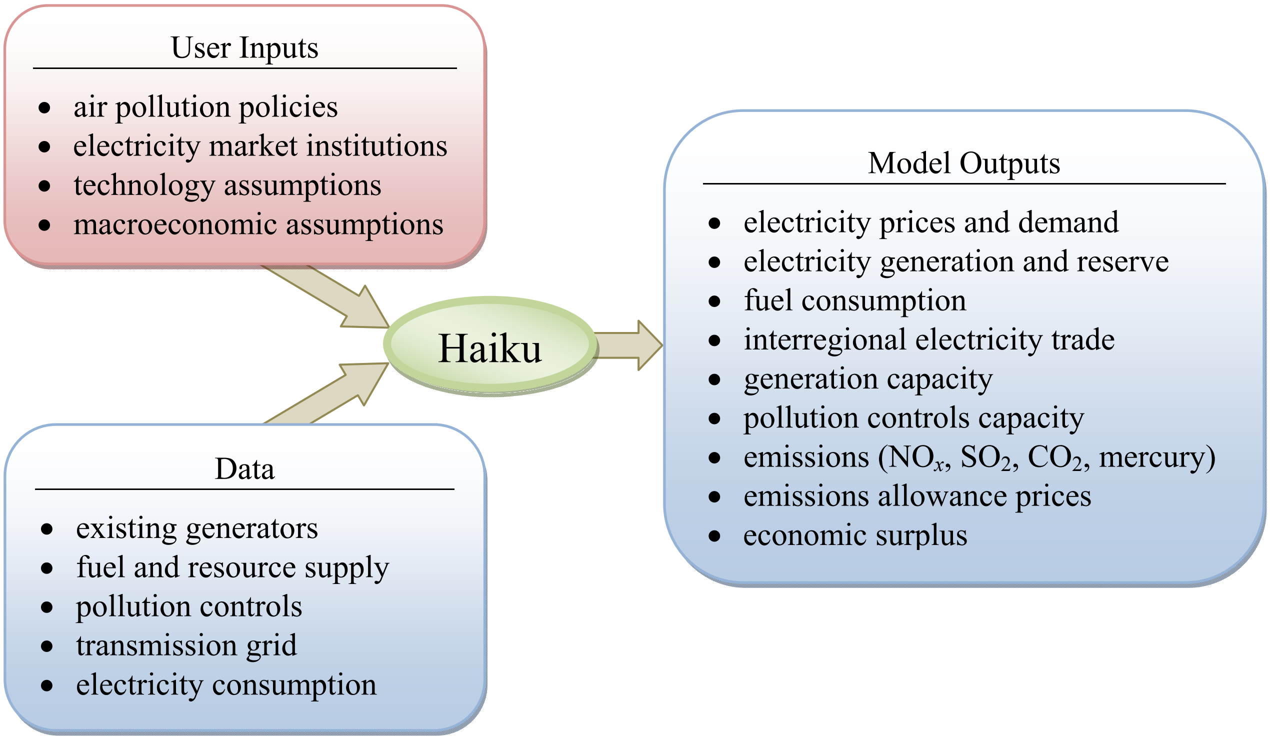
[1] As of January 2009, the model is initialized to the state of the U.S. electricity sector in the year 2004.

Figure 1. Overview of Haiku Information Flow



The mathematical program that Haiku solves is a zero-finding problem. The model iterates to find an equilibrium in the spatially and temporally linked electricity markets that achieves simultaneous compliance with a large set of constraints. These constraints are designed to identify the minimum cost strategy for operation and capacity planning of the electricity system to satisfy price-responsive electricity demand functions given a wide set of regulatory institutions. The structure of the institutions is flexible and is defined by the user to simulate alternative scenarios of policy implementation. Scenarios may also vary to reflect uncertainty in underlying assumptions about the future, such as future weather patterns and behavior of fuel markets.

In the absence of market power or other strategic behavior, the minimum cost solution found by Haiku is also the profit maximizing solution for electricity producers. The electricity demand functions in Haiku are econometrically estimated to determine the extent of price responsiveness of electricity consumers who are assumed to be utility- (residential class) and profit- (commercial and industrial classes) maximizers, conditional on contemporaneous prices and without regard for expectations of future prices. The solution to the Haiku model therefore falls short of social welfare maximization within the electricity sector to the extent that real world electricity consumers do take account of future market condition when determining short-run demand. Since the model covers only the electricity sector, social welfare across all sectors of the economy is not measurable in the model.

Structure of the Model

Model Plants and Regions

Electricity generation capacity in Haiku is characterized across two dimensions: Model Plant (MP) and Haiku Market Region (HMR). The MP dimension distinguishes generation capacity primarily according to technical characteristics while the HMR dimension captures geographic location. Each generator is sorted into the MP dimension across a set of characteristics including prime mover (the generator technology), fuel type, vintage, and geographic location with respect to coal mines and installed pollution controls (for coal plants only). This sorting is designed to make the model computationally feasible while preserving the essential differences among generators that are relevant to the types of policy questions asked of the model. Because this aggregation necessitates the representation of the cost and performance parameters of the generators that comprise an MP at the averages of the constituent generators, the set of MPs is constructed to minimize the total capacity of the largest MP, thereby reducing the error introduced by representing generators at their MP averages.

Data from the EIA on the characteristics of the generator unit inventory in the continental United States are used to map each generator to a unique HMR/MP pair. Haiku simulates electricity markets into the future and accounts for projected investments in generation capacity as MPs separate from those that correspond to the capacity existing in the EIA data. The MPs for new investments are parameterized based on projections of cost and performance and account for emissions abatement technologies required under New Source Performance Standards. The new MPs typically are more efficient than the corresponding existing MPs. Table 1 shows the list of model plants with those corresponding to existing generators in the top part of the table and those corresponding to new investments in the lower part of the table. The first column shows MP groupings by prime mover and fuel type. The second and third columns describe the number and nature of the MPs employed in Haiku to represent the generators described in the first column.

The cost and performance parameters of each model plant are specified exogenously for a data initialization year (see footnote 1 for more on the data initialization year). The nameplate capacity of each existing model plant is defined for the data initialization year according to Equation (1). Model plants corresponding to new investments are assigned a capacity of zero in the data initialization year.

$$N_k = \sum_i NG_i f(i,k) \tag{1}$$

where,
N_k = nameplate capacity of MP k [MW],
NG_i = nameplate capacity of generator i [MW],
$f(i,k)$ = 1 if generator i maps to MP k, 0 otherwise.

There are other exogenous parameters, in addition to nameplate capacity, associated with each model plant. These parameters characterize the costs and technical characteristics of the model plants and are calculated as averages, not as aggregates, over the values observed for each generator.[2] The cost parameters are variable O&M (operations and maintenance) cost, fixed O&M cost, and capital cost. The technical parameters are planned and forced outage rates, heat rate, the ratio of operating capacity to nameplate capacity in each season, baseline emission rates for NO_x, SO_2, CO_2, and mercury[3], and fuel costs for municipal solid waste (MSW) and landfill gas powered generators. Equation (2) shows the method used for calculating the cost and technical parameters for each existing model plant as a nameplate capacity weighted average of the parameters for the individual generators that comprise the model plant.

$$P_k = \frac{\sum_i NG_i f(i,k) P_i}{\sum_i NG_i f(i,k)} \tag{2}$$

where,
P_k = value of cost or technical parameter for MP k [varies],
NG_i = nameplate capacity of generator i [MW],
$f(i,k)$ = 1 if generator i maps to MP k, 0 otherwise,
P_i = cost or technical parameter for generator i [varies].

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[2] For new model plants, the cost and technical parameters are not derived from the existing generator unit inventory. They are assigned for the initialization year as described in Table 2.

[3] Emission rates for SO_2, CO_2, and mercury are not assigned to coal-fired generators this way. They are determined endogenously depending on the type of coal chosen to fuel the associated boiler(s).

Table 1. Model Plants

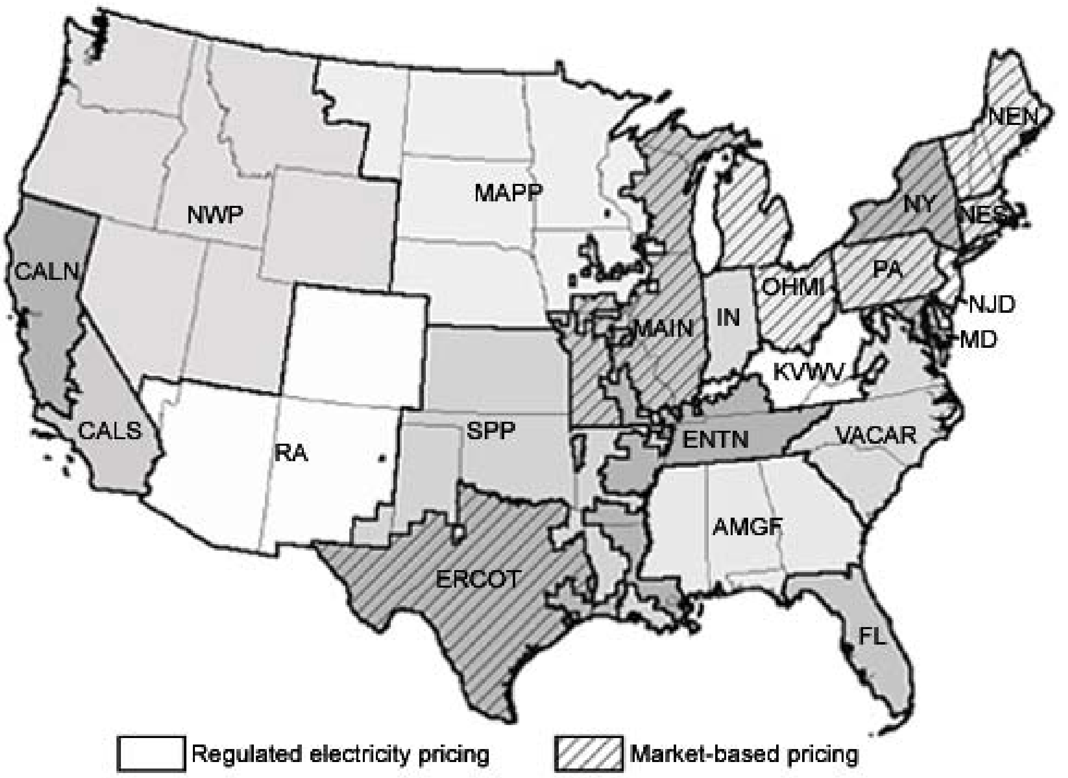
	MP Prime Mover and Fuel Type	# of MPs	Other Dimensions of MP Specification
Existing	Steam : Coal	15	types of pollution control installed feasibility of pollution control retrofit geographic location relative to sources of coal supply
	Steam : Natural Gas	4	types of pollution control installed vintage
	Steam : Nuclear	2	vintage
	Steam : Oil	1	
	Steam : Biomass	1	
	Steam : Geothermal	1	
	Combined Cycle : Natural Gas	1	
	Combined Cycle : Oil	1	
	Combustion Turbine : Natural Gas	2	vintage
	Combustion Turbine : Oil	2	vintage
	Hydro : Conventional	1	
	Hydro : Pumped Storage	1	
	Wind	1	
	Solar	1	
	MSW / Landfill Gas	1	
	Existing Subtotal	35	
New	Steam : Coal	3	geographic location relative to sources of coal supply
	Steam : Nuclear	1	
	Steam : Geothermal	1	
	IGCC : Coal	1	
	IGCC : Biomass	1	
	Combined Cycle : Natural Gas	2	conventional/advanced technology
	Combustion Turbine : Natural Gas	2	conventional/advanced technology
	Wind	1	
	Solar	1	
	Landfill Gas	1	
	New Subtotal	14	
	Existing & New Total	49	

Over the simulation horizon, the generation capacity of each model plant can change as existing generators are retired and new generators are constructed. The cost and technical parameters evolve from the levels in the data initialization year according to rates that reflect technological improvement. A discussion of technological improvement in new investments is in the section on Technological Learning.

Each model plant is located in one of 21 HMRs that divide the lower 48 states of the United States as illustrated in Figure 2. In some cases these regions correspond to the North American Electricity Reliability Council (NERC) subregions or the Electricity Market Model regions as defined in the National Energy Modeling System (NEMS), which is maintained by the EIA. In others, especially in the Northeast, model plants are aggregated into smaller regions that correspond to states or small groups of states to allow for policy analysis at finer levels of detail. Canada is treated in the model as an aggregate entity with which limited power trading is permissible. There is no power trading with Mexico represented in Haiku. See Chapter 3 for more details on the modeling of interregional power trading.

The model user has flexibility in defining the mapping of generators into model plants and regions. This flexibility is not an off-the-shelf feature of the model, but it is achievable with moderate effort. This capability allows the model to evolve as the landscape of policy relevant issues evolves. Since the initial version of Haiku was developed in 1998, the configuration of model plants and regions has been refined numerous times.

Figure 2. Mapping of States and Regions



Note: The pricing regimes indicated are the default settings in Haiku, but can be defined by the user.

Seasons, Time Blocks, and Customer Classes

Electricity demand and the corresponding electricity generation and reserve services are represented in Haiku in energy space (MWh), not in power space (MW). The computational impossibility of modeling electricity markets in power space for every moment in time necessitates this method. Each year is divided into twelve groups that correspond to three seasons and four time blocks within each season.

The three seasons are modeled as summer, winter, and spring/fall. Summer is a five-month season from May to September that conforms to the ozone season in the eastern United States. Winter is a three-month season including December, January, and February. Spring/fall is a four-month season including March and April, and October and November. This mapping between months and seasons is chosen not only for the ozone season correspondence in the summer, but also because it provides a good correspondence with the annual cycle of electricity demand. The highest level of demand tends to be in the summer and another peak occurs in the winter. The troughs that typically occur in spring and fall tend to be of similar magnitude.

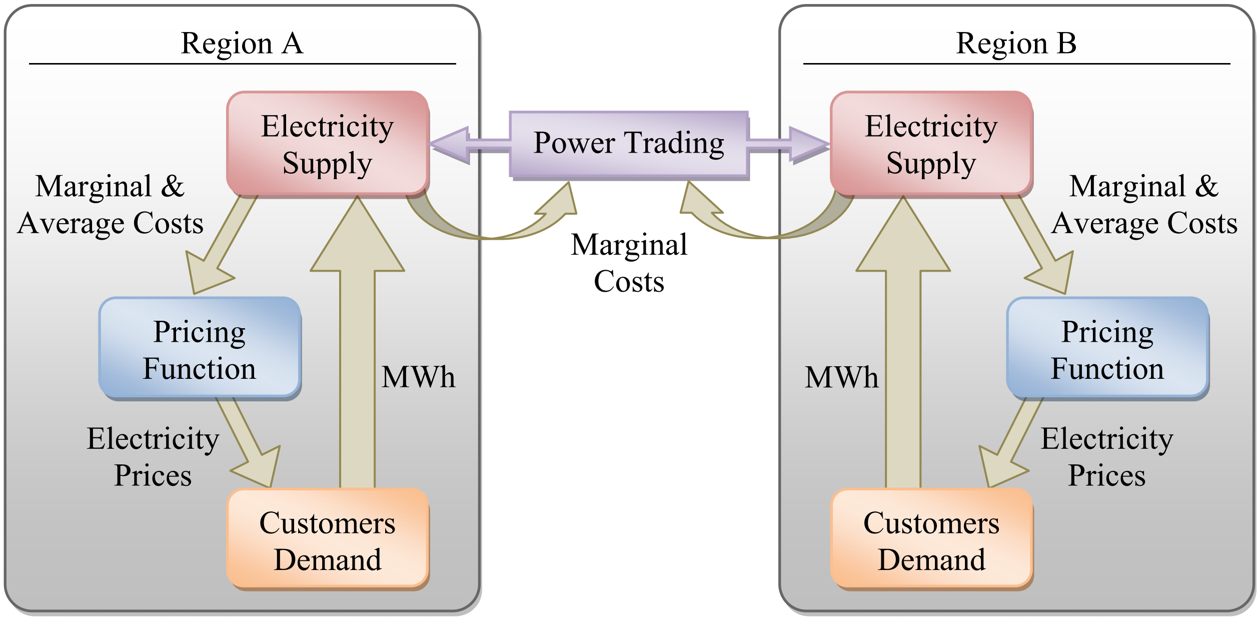
Within each season, hours are separated into four time blocks that reflect the level of aggregate electricity demand. The time blocks are named baseload, shoulder, peak, and superpeak. The baseload time block includes the 70 percent of the hours in the season that have the lowest electricity demand. The shoulder includes the next 25 percent of hours. The peak includes the next 4 percent, and the superpeak includes the final 1 percent of hours in each season.

The total demand for electricity in each region, season, and time block is aggregated from demand that is calculated separately for three customer classes: residential, commercial, and industrial. Each customer class is modeled with a separate demand function that is independent of the demand functions for the other customer classes. For details on the Haiku electricity demand functions, see Chapter 3.

Supply, Demand, and Interregional Power Trading

Haiku simultaneously identifies a set of electricity market equilibria across all simulation years, HMRs, seasons, time blocks, and customer classes. On the supply side, generation capacity is represented by model plants that minimize production costs over the short run by scheduling their operations and over the long run through investment and retirement. The model plants are contemporaneously linked by markets for fuel and linked through simulation years by long-lived generation capital. Another link through years is established on the demand side by a reduced form demand model with a partial adjustment specification that captures the dynamic effects of choice regarding the efficiency of electricity end-use capital. The details of these algorithms are described in Chapter 3.

Figure 3. Schematic of Market Equilibrium in a Single Season, Time Block, and Simulation Year



For a single season and time block within a simulation year, Haiku identifies a production schedule, electricity prices and consumption, and an interregional power trading pattern that simultaneously clear the markets. Figure 3 is a schematic illustrating the relationships that determine the equilibrium. Given a level of electricity demand in each region, the supply side of the electricity sector returns the marginal and average costs of electricity production including the costs for both generation and reserve services. These costs are transformed into electricity prices by a pricing function, which can take the form of cost-of-service regulation or wholesale competition. Electricity customers demand power based on these prices. Simultaneous satisfaction of the constraints in each of the three nodes establishes electricity market equilibrium in a single region.

Market equilibrium between regions is also illustrated in Figure 3. Haiku represents the national transmission grid as a set of potential bilateral trades between every pair of contiguous regions. Nationwide cost minimization leads to the equilibration of marginal production costs[4], illustrated in the "Power Trading" module, between each contiguous pair of regions with sufficient transmission capability. Between pairs with insufficient transmission capability,

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[4] The marginal costs that equilibrate are adjusted for interregional transmission costs and line losses. Intraregional transmission costs and line losses are accounted within the supply side module in each region.

marginal costs cannot equilibrate and Haiku assigns a price for trades on the constrained line that is the average of the marginal costs in each region. For regional pairs that are not contiguous, no direct power trading is allowed. However, power trades between noncontiguous regions may be executed through intervening regions that connect the noncontiguous regions. Interregional line losses and transmission costs are accounted in a pancake manner; that is, a power trade which crosses multiple regional boundaries faces losses and costs at each boundary. A nationwide equilibrium is established when each contiguous pair of regions is in equilibrium across the transmission line connecting them and each individual region has established equilibrium between the supply and demand sides according to the pricing function. Detailed descriptions of intraregional and interregional market equilibria are located in Chapter 3.

The pricing functions and demand functions illustrated in Figure 3 are explicit functions, but the supply side is an implicit function that depends on a set of integrated modules. Haiku endogenously determines many of the supply side characteristics, including generation capacity and installed pollution abatement technologies for each model plant, fuel prices, scheduling of outages for maintenance, constrained dispatch of hydroelectric generators, and prices for air pollution abatement policies. Some of the technical characteristics of the model plants are also endogenous, though the model does not optimize on them. Chapter 3 sets forth the details of these modules.

Control Variables, Iteration, and Convergence

The Haiku model uses an iterative convergence algorithm to find an overall equilibrium involving 17 control variables that contain about 80,000 individual elements. Each element in each control variable has an equilibrium value that depends on the values of all of the other elements in all of the other control variables. Each control variable is adjusted iteratively in response to the values of the other control variables. Equilibrium is defined as the state in which all control variables are simultaneously the best response to the values of all other control variables. Exact equilibrium is never achieved so convergence criteria are applied to determine when adequate precision is achieved. Typically, the criterion is that changes in each control variable between iterations of the model must be less than one percent of the level of the variable. The possibility that the model solution is not unique is mitigated by confirming that equivalent solutions are obtained from different initial conditions.

Data Overview

The data in Haiku come from a variety of mostly public sources, which are listed in Table 2. The EIA is a primary source of data on the performance characteristics of many of the generation technologies represented in the model. In addition, the EIA is used for information about fuel supply. The U.S. Environmental Protection Agency (EPA) provides important information about pollution control technologies. In some cases this information is supplemented with information from the NERC, and in other cases firms have shared proprietary data or we have supplemented information from our own research.

Table 2. Haiku Data Sources

Variables	Source
Existing Generators	
Capacity	EIA
Heatrate	EIA
Fixed and variable O&M cost	FERC\EIA\EPA
Existing pollution controls	EPA\EIA\RFF
Planned pollution controls	RFF
Baseline emission rates	EPA (CEMS/NEEDS)
Scheduled and unscheduled outage rates	NERC GADS data
New Generators	
Capacity	EIA\EPA
Heat rate	EIA\EPA
Fixed and variable operating cost	EIA\EPA
Capital cost	EIA\EPA
Outage rates	EIA\EPA
Fuel Supply	
Wellhead supply curve for natural gas	Interpolated based on EIA forecasts
Delivery cost for natural gas	EIA (AEO 2007)
Minemouth supply curve for coal	EIA (AEO 2007)
Delivery cost for coal	EIA (AEO 2007)
Delivered oil price	EIA (AEO 2007)
Pollution Controls	
SO_2—cost and performance	EPA
NO_x—cost and performance	EPA
Mercury—cost and performance	EPA
Transmission	
Interregional transmission capability	NERC/ICF IPM inputs
Inter and intraregional transmission costs	EMF
Inter and intraregional transmission losses	EMF
Demand	
Demand level (by season and customer class)	EIA
Load duration curve	RFF
Demand growth (by customer class and region)	EIA (AEO 2007)
Demand elasticity (by customer class)	Estimated by RFF

2. Institutions

Haiku is designed to simulate changes in electricity markets. Particular attention is paid to modeling changes in how electricity prices are determined in electricity markets and in the environmental regulations that govern them. Changes in these market and regulatory institutions affect the incentives and the economic behavior of participants in the markets, including producers of electricity and reserve services, transmission grid owners, and electricity consumers. In turn, changes in incentives affect various output measures such as electricity price and environmental performance of the market. This chapter will detail the capabilities of Haiku for modeling different types of market structures and environmental policies.

Market Structure

The passage of the Energy Policy Act of 1992 unleashed a process that changed the regulatory and market structures of the U.S. electric power industry. The act called on the Federal Energy Regulatory Commission (FERC) to order all transmission-owning utilities to open access to their transmission systems at nondiscriminatory, cost-based transmission rates to facilitate competitive wholesale power transactions. Many states followed up with legislation and regulations that opened up retail markets to competition as well. Figure 4 provides a summary of the status of electricity market restructuring across the nation as of 2007.

The structural details of electricity markets vary widely across the nation. The model categorizes all markets as either regulated or competitive. In regulated markets, prices have traditionally been set based on average cost of service and this is the approach adopted in the model.[5] In competitive markets, prices are based on the marginal cost of service. Haiku treats each region of the country as either regulated or competitive when solving for equilibrium electricity prices. In many cases, the states that comprise a region do not all share a single market structure. In such cases, Haiku uses the market structure that characterizes the states that comprise a majority of the population within the region.

The remainder of this discussion of market structure will describe the Haiku algorithms for pricing electricity under regulated pricing and under competition, the refinements to these general models, and the effects of competition on technical parameters.

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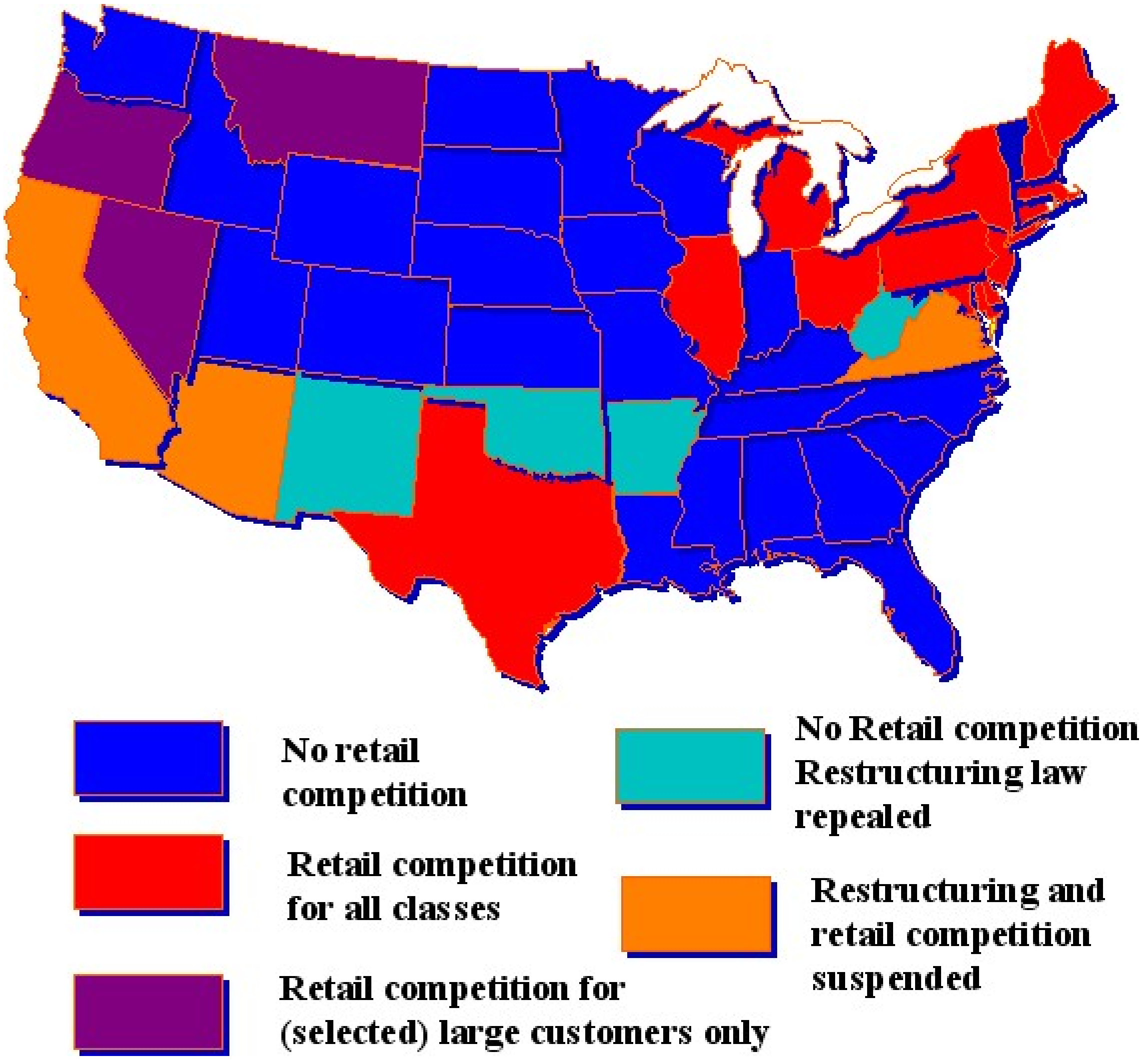
[5] Another approach to price regulation that has been used in some states is price cap regulation that essentially sets a cap on prices that regulated firms can charge.

Figure 4. Status of Electricity Market Restructuring, 2007



Source: Joskow 2008.

Regulated Pricing (Average Cost Pricing or Cost-of-Service Pricing)

The traditional method employed by state public utility commissions (PUCs) for pricing electricity is to calculate the average cost of providing electricity services to each customer class and set electricity prices accordingly. In the model, this approach is called regulated pricing. Haiku models regulated pricing by breaking electricity services into two primary components. The production component accounts for generation and reserve services and the delivery component accounts for transmission and distribution services (T&D). Each component includes fixed and variable costs that are allocated across sales units (denominated in MWh). Retail electricity prices are adjusted from the sum of these two components to correct for the portion of profits garnered in the interregional power trading market that is assigned to consumers in the regulated regions. Prices are also adjusted from the annual average according to the historical deviations of prices in each month from the annual average price.

The average cost of the production component of electricity supply is calculated on an annual basis and includes variable and fixed production costs, including capital costs. Because each customer class has a unique distribution of demand across time blocks, annual average production costs may vary by customer class. However, Haiku calculates the production component of electricity prices as the annual average cost of production to meet demand from all customer classes and assigns this value uniformly to all customer classes. The delivery component of electricity service costs is treated as constant throughout the year, but does explicitly vary by customer class, with industrial customers paying a lower price because they tend to draw power at higher voltages and thus rely less on the distribution grid.[6] Commercial customers pay a higher price and residential customers pay the highest price. Electricity price is then set according to the sum of the annual average costs of electricity production and delivery for each customer class (adjusted for historical monthly variation). For a single regulated region (ignoring power imports and exports), the equilibrium electricity price is that which solves Equation (3).

$$P_i = \frac{K + \sum_j V_j}{\sum_{i,j} D_{ij}\left(P_i\right)} + T_i \tag{3}$$

where,

P_i = electricity price for customer class i [\$/MWh],
$D_{ij}(P_i)$ = demand for electricity from customer class i in time block j at price P_i [MWh],
K = regional fixed costs of generation capacity, including annualized capital cost [\$/yr],
V_j = variable costs incurred for generation and reserve services in time block j [\$],
T_i = charge for T&D for customer class i [\$/MWh].

The retail electricity prices faced by consumers are adjusted from the prices defined by equation (3) to correct for the proceeds from interregional power trading. A producer that sells

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[6] Another reason prices might vary by customer class is that state public service commissions, which have authority for setting prices, have discretion in setting prices to promote economic development or attract business. This can lead to prices differentiated by customer class. Because these policies tend to be idiosyncratic, and also to vary among states within Haiku's regions, they are not represented explicitly.

power to a customer outside of the region where the producer is located will collect rents, defined as the difference between revenues and costs. The user of the model must specify how these rents will be divided between the producers and the electricity consumers within the exporting region. The default setting in the model assigns all of the rents to consumers.

A second adjustment to the retail electricity prices faced by consumers accounts for model calibration. A discussion of calibration is presented in Chapter 3.

Competitive Pricing

In regions with competitive electricity markets, the retail price of electricity is modeled as the sum of three components: generation price, reserve price, and a T&D charge. The treatment of T&D in competitive regions is identical to its treatment in regulated regions; that is, T&D is a fixed charge for each customer class expressed in $/MWh that equals the average cost of T&D services and does not vary throughout a year.

Generation prices in competitive regions are simply equal to the marginal cost of generation in each time block. Marginal cost in a time block consists only of the variable costs that would be avoided by the marginal unit were it to abstain from generating in the time block. The degree to which other costs (such as fixed operation and maintenance costs as well as capital costs) are loaded into marginal cost is an empirical matter. Haiku uses a default assumption that no costs other than variable are loaded into marginal cost. For a detailed breakdown of the variable cost components of marginal cost, see the section on Production in Chapter 3. Generation prices vary by time block, but not by customer class within a time block.

Haiku solves for an equilibrium payment for reserve services, which is termed the reserve price and is analogous to capacity payments that exist in various forms in competitive regions. The reserve price reflects the scarcity value of capacity in each time block. As such, it is like the generation price in that it varies by time block, but not by customer class within a time block. Given an equilibrium set of generation prices and reserve prices, the reserve price in any single time block is set just large enough to prevent the marginal provider of reserve services in the time block from retiring. This calculation accounts for costs incurred and revenues garnered by this marginal unit in all other time blocks. In equilibrium, the reserve prices in baseload time blocks typically are equal to zero. The reserve prices in other time blocks are generally positive with the highest prices in the superpeak time blocks, especially in the summer. The treatment of reserve prices in producer accounting of revenues and profits is addressed under Capacity Investment and Retirement in Chapter 3.

In competitive regions, retail electricity prices can vary in time through the application of time-of-use pricing. Time-of-use pricing allows the retail electricity price to vary during a single season or even a single day according to a predetermined schedule that is known to the consumer. Haiku allows time-of-use pricing to be implemented for individual customer classes within any region that is modeled under competitive pricing. Customer classes that do not have time-of-use pricing face the same three components of electricity price as those that do have time-of-use prices, but the components are averaged over all time blocks within a season for each customer class. This yields prices that vary by season, but not by time block within a season. Ignoring interregional power trades, the equilibrium electricity prices for customer classes that do not face time-of-use pricing are those which solve equation (4).

$$P_{ik} = \frac{\sum_{j} D_{ij}\left(P_{ik}\right)\left(G_{j} + R_{j}\right)}{\sum_{j} D_{ij}\left(P_{ik}\right)} + T_{i} \tag{4}$$

where,

P_{ik} = electricity price for customer class i in season k [\$/MWh],
$D_{ij}(P_{ik})$ = demand for electricity from customer class i in time block j at price P_{ik} [MWh],
G_j = generation price in time block j [\$/MWh],
R_j = reserve price in time block j [\$/MWh],
T_i = charge for T&D for customer class i [\$/MWh].

An important distinction exists between wholesale competition and retail competition in electricity markets in the United States. Today there are many customers for whom retail electricity prices are regulated, but the power companies who provide those regulated retail services compete for electricity procurement in a competitive wholesale market. This market structure is simulated in Haiku as a competitive market without time-of-use pricing. The institutional assumption that underlies this modeling approach is that electricity retailers will be recompensed on a cost-of-service basis as if they must procure all of their electricity in a competitive wholesale market that has equilibrium prices set at the marginal cost of generation. The default assumption is that retail electricity prices can vary by season, but not within a season, as it is defined in equation (4). There are virtually no customers in the United States today who face time-of-use pricing under retail competition, but this capability is functional in Haiku and can be used to project a scenario in which customers are equipped with meters for measuring the timing of electricity consumption.

Effect of Market Structure on Technical Parameters

Competition in the electricity industry is expected to quicken the pace of technological change. Productivity change that results from restructuring is implemented in the model through changes in four parameters: improvements in the availability factor at all generators, reductions in the heat rate at existing fossil fuel and nuclear fired steam boilers, reductions in operation and maintenance costs at all existing generators, and reduction in general and administrative costs at all generators. The rates of productivity change resulting from restructuring have two components. First, Haiku assumes that a region that has just moved to competitive pricing will reap rapid improvements for two years. Second, the entire country will observe a smaller rate of improvement as a function of the proportion of the country that has implemented competitive pricing. As the proportion of the country implementing competitive pricing grows, the rate of improvement in these four parameters grows. This component of productivity improvements reflects the common availability of technology and the common investment climate shared by firms in different regions.

Environmental Policies

The Haiku model can simulate a range of different types of environmental policies affecting the emissions of NO_x, SO_2, CO_2, and mercury from the electricity industry and the techniques employed by the industry to abate emissions. Among the environmental regulatory methods that the model is equipped to handle are cap-and-trade programs for emissions allowances, technology standards, post-combustion emissions control performance standards, and emissions taxes. Particular flexibility is available for modeling emissions allowance trading programs with capabilities including allowance banking, alternative methods of allowance allocation, safety valves on allowance prices, allowance caps that rely on circuit breakers, and allowance offsets for CO_2 emissions. Haiku is also equipped to model policies specific to renewable technologies including renewable portfolio standards and renewable energy production credits.

This section provides detail on the modeling techniques employed to simulate environmental policies. For details on the algorithms used to simulate emissions and abatement techniques, please see the discussion of Pollution Controls in Chapter 3.

Emissions Allowance Trading

Cap-and-trade programs for emissions allowances have become the gold standard for emissions regulation in the electricity industry. This regulatory approach establishes a cap on aggregate emissions and issues allowances for each unit of emissions up to the cap. Individual facilities are required to surrender one allowance for every unit (e.g. ton) of emissions, but retain compliance flexibility across a combination of emissions reductions and allowance acquisition. As all facilities retain this flexibility, the expectation is that emissions reductions sufficient to satisfy the aggregate cap will occur at the facilities that can reduce at the lowest unit cost. These facilities thus incur an emissions abatement cost, but avoid allowance costs for each unit of emissions abated. Other facilities avoid abatement cost, but at the expense of greater allowance costs. This textbook outcome is an economically efficient means by which to achieve any level of emissions. There are numerous variations in cap-and-trade programs, and most of them can be represented in the Haiku model, as described in the following sections.

Allowance Prices and Banking

The fundamental element in the emissions trading algorithm is the allowance price. Many other components in the model take the solution to the allowance price algorithm as an input that affects incentives and behavior. These components include the algorithms for generation dispatch and investments in pollution controls. Haiku also is capable of modeling emissions taxes. The model treats an emissions tax as equivalent to an allowance trading program with an exogenously specified allowance price. Because emissions taxes can be modeled as a special case of an allowance program, no more discussion will be devoted to taxes.

Under the simplest type of allowance trading policy, Haiku simply finds the allowance price that, in equilibrium, yields annual emissions equal to annual allowance allocation. Any combination of the Haiku regions may be aggregated under a single cap-and-trade or allowance trading policy and any combination of model plants may be designated as requiring an allowance for each unit of emissions. The model is equipped to handle policies in which the number of allowances required per unit of emissions varies by season. This is managed by multiplying seasonal emissions by a coefficient reflecting the number of allowances required per unit emissions in each season. It is in this manner that Haiku can simulate the NO_x SIP Call policy, which applies only to emissions between May and September. The coefficient for the other months is set to zero.

A common feature of allowance trading is the ability to bank allowances for use in a future compliance period. The Haiku allowance-banking algorithm is built on the Hotelling rule from natural resource theory (Hotelling 1931). This rule states that a non-renewable resource, like oil, will be extracted at a rate that causes the price for the resource to rise at a rate equivalent to the discount rate of the producer. The reason that one might expect this to be true is simply that if the price of the resource were to rise at a different rate, the owner of the resource could make money by leaving the oil in the ground, or alternatively extracting it all at once. If the entire industry behaved in this way, then prices would adjust until, in equilibrium, the rate of change in price equals the discount rate.

A version of the Hotelling rule is expected to apply to emissions allowance banking because allowances can be treated as the nonrenewable resource with a fixed allocation that will be priced according to the allowance consumption rate of the electricity industry. As such, the bank will be built up and then drawn down at a rate that causes allowance prices to rise at the discount rate of the electricity producers. When the quantity of allowances in the bank is zero, the allowance price may rise at a rate slower than the discount rate because the bank is not permitted to have a negative balance. However, the allowance price may not rise at a rate faster than the discount rate.

Haiku applies the Hotelling rule to emissions allowances by bounding the solution to an allowance policy that does not allow banking. In equilibrium, the model has solved for the date at which the allowance bank begins to accumulate, the date at which it is exhausted, and the allowance price at the moment of exhaustion. The allowance price in all years prior to the initiation of the bank must be rising at no more than the discount rate. Between bank initiation and exhaustion, the allowance price must rise at a rate exactly equal to the discount rate. After bank exhaustion, the model permits the bank to be reinitiated. So the period after bank exhaustion is identical to the period before bank initiation and thus the allowance price must rise at a rate no greater than the discount rate.

Emissions allowances under banking are likely to be owned while are they banked by entities outside of the electricity sector, such as banks. Haiku explicitly tracks allowance ownership by each model plant and by a generic third party investor. This allows for a precise measure of the time path of revenues earned and costs incurred from an allowance market with banking. These costs and revenues can affect the capacity investment and retirement decisions made by generators.

Allowance Allocation

One of the most important components of any emissions allowance trading program is the initial allocation of allowances. Haiku is capable of modeling most of the various allocation methods currently under consideration in policy discussions. Allowance allocation is treated in two steps. First is the assignment of the level at which the allowance allocation decision is made, and second is the allocation decision itself. At the first step the allowance allocation decision can be centrally determined by the administrator of the trading program or the administrator can apportion the allowances to constituent regions. In the case of regional apportionment, each region is free to choose its own allocation method. An example of centralized allocation is the SO_2 trading program under Title IV of the 1990 Clean Air Act Amendments in which the federal government stipulates that the SO_2 allowances will be forever grandfathered to a set of facilities using a formula identified in the statute. An example of regional apportionment is the Regional Greenhouse Gas Initiative (RGGI) in which each state that is a party to the agreement is apportioned a quantity of allowances that they may allocate to electricity generators (or anyone else) at their discretion, subject to guidelines set forth in the model rule.

The second step to specifying the mechanics of emissions allowance allocation in Haiku is the allocation method itself. The five methods supported in the model are *cap-and-dividend*, *grandfathering*, *updating*, *load-based*, and *incentives for end-use efficiency*. The cap-and-dividend, load-based, and end-use efficiency methods include an allowance auction followed by governmental redistribution of allowance revenues. Under these methods, electricity generators must purchase allowances either at auction or in the secondary allowance market. For any bundle of allowances, any two of these methods may be specified in any proportion for each simulation year. Thus a policy that incorporates a gradual shift from grandfathering to an auction, for example, can be modeled by Haiku. Others methods of allocation, such as allocation to research and development of carbon capture and sequestration technology, allocation of bonus allowances for clean technology deployment, and allocation to low-income households are not currently supported in the model.

Under a *cap-and-dividend* allocation, allowances are sold at auction to any entity that wishes to buy them at the market price determined by the auction. The authority that administers the auction collects the revenues and then recycles them to the citizenry as a lump-sum transfer. This is equivalent to treating the allowance revenue as an unassigned public good; that is, each dollar counts as a dollar in the calculation of economic welfare. In practice, an auction is a likely component of other methods of allocation such as load-based allocation and incentives for end-use efficiency. These methods are treated as distinct from cap-and-dividend because they have direct effects on electricity markets that distinguish them from a lump-sum transfer type of allocation.

Under *grandfathering*, allowances are given for free to a set of recipients whose shares are determined according to some historical measure. The historical measure is determined prior to the imposition of the cap and is fixed for all time. The agent responsible for allocating grandfathered allowances must determine both the set of eligible recipients as well as the basis upon which allowances are allocated. The set of eligible allocation recipients need not be identical to the set of generators responsible for compliance with the program. The basis for allocation can be specified as electricity generation, emissions of regulated pollution, or heat input.

Updating allocation is a system by which allowances are given for free to a set of recipients based on a metric that is continually updated. A standard metric is each facility's share of recent electricity generation. For example, allowance allocation in year *t* could be determined based on generation in year *t*-2. Updating allocation based on generation introduces an incentive to generate beyond that which would exist under a cap-and-dividend or grandfathering allocation because generation earns a future allocation of valuable allowances[7]. Haiku is configured to accommodate any set of model plants for allowance allocation eligibility and for a lag of any duration between the year in which output is measured and the year in which it earns an allocation. One refinement to the updating allocation method available in Haiku is for allowance allocation to be awarded only to incremental changes in output; that is, the model can be configured to allocate allowances to generators only on the basis of output that exceeds output in some benchmark year.

Load-based allocation is a method designed to recognize the public ownership of the property right assigned to clean air. This method of allowance allocation is implemented in Haiku as a reduction in electricity prices sufficient to exhaust all revenues that would be garnered from an allowance auction. In practice, load-based allocation would likely take the form of an allowance auction in which revenues are apportioned to local distribution companies. To the extent that the retail electricity prices charged by local distribution companies to their customers are regulated, the regulator is able to enforce an electricity price reduction sufficient to exhaust the auction revenues received by each company. Currently, almost all residential consumers and the majority of commercial and industrial consumers in the United States buy electricity from a regulated local distribution company. As Haiku does not explicitly distinguish wholesale and retail markets for electricity, load-based allocation is implemented for each customer class designated to receive an allowance allocation as if retail rates are regulated.

Allocation to *incentives for end-use efficiency* is a prominent feature of the RGGI program and of many recent federal proposals for greenhouse gas emissions mitigation. The algorithm for modeling incentives for end-use efficiency funding is called the demand

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[7] An updating allocation based on emissions can, under some plausible conditions, not introduce the distortionary incentives that are introduced under an updating allocation based on generation. See Rosendahl et al. 2008.

conservation incentive (DCI) and is integrated into the Haiku demand system. A description of the DCI is in Chapter 3. This type of allowance value allocation is similar to others that earmark funds for specific uses that reinforce the goals of the climate policy and reduce the cost of compliance. Allocation to end-use efficiency lowers compliance costs because it reduces electricity demand and generation and therefore reduces allowance scarcity and lowers allowance prices. Aside from end-use efficiency, proposals have emerged that provide funding for research and development in carbon capture and sequestration technology and in electricity generated by renewable resources. These examples of directed funding allocation methods are not currently supported in Haiku.

Each of the five allowance allocation methods supported in Haiku has distinct effects on electricity markets. In particular, allowance cost pass through from electricity generators to electricity prices faced by consumers can vary from one method to the next and can do so differently depending upon the regulatory structure that governs wholesale electricity markets. These differences are illuminated in Table 3. The absence of allowance cost pass through is a subsidy to electricity consumption, which in competitive regions distorts prices away from the economically efficient level where they are equivalent to the marginal cost of production. In regulated regions the efficiency effects of the subsidy are not known *a priori* and depend upon the relationship between marginal and average costs.

Table 3. Allowance Cost Pass Through to Electricity Prices

Allowance Allocation Method	Wholesale Market Regulatory Structure	
	Regulation	Competition
Cap-and-dividend	Yes	Yes
Grandfathering	No	Yes
Output-based	No	Yes
Load-based	No	No
End-use efficiency	Yes	Yes

Safety Valve and Circuit Breaker

Uncertainty is a constant for policymakers crafting policy with long-term implications. Global climate change policy is one such issue for which uncertainty threatens to incapacitate the policy process. Among the many policy instruments being considered to manage the costs and benefits of reducing greenhouse gas emissions in the United States from the electricity sector are a "safety valve" and a "circuit breaker." Both of these policy instruments are designed as variants to the textbook carbon allowance cap-and-trade program to bring a prescribed regulatory response to as yet unrealized circumstances in a carbon allowance market.

A safety valve serves as a ceiling on the price of allowances by increasing the provision of allowances when the price of allowances exceeds the safety valve level. A symmetric safety valve in which there is also a floor on the price of allowances that can be managed by retracting some allowances from the market has also been proposed. Haiku models both a safety valve ceiling and floor by finding the equilibrium number of allowances that must be added to or removed from the market to prevent the allowance price from breaching the bounds defined by the safety valve. The model is also capable of simulating a policy that constrains the number of allowances that can be issued or retracted under a safety valve. When a constraint on safety valve allowances is binding, the price for allowances may breach the ceiling or floor defined by the safety valve, but will do so by less than it would have in the absence of a safety valve.

A circuit breaker is a policy in which the stream of allowance provisions depends on the realization of allowance prices. Haiku models a circuit breaker as an initial provision of allowances followed by an annual reduction in the allowance provision. This annual reduction is short-circuited if the allowance price exceeds the circuit breaker price. Haiku is not equipped to model a circuit breaker floor that could yield an accelerated reduction in allowance provision.

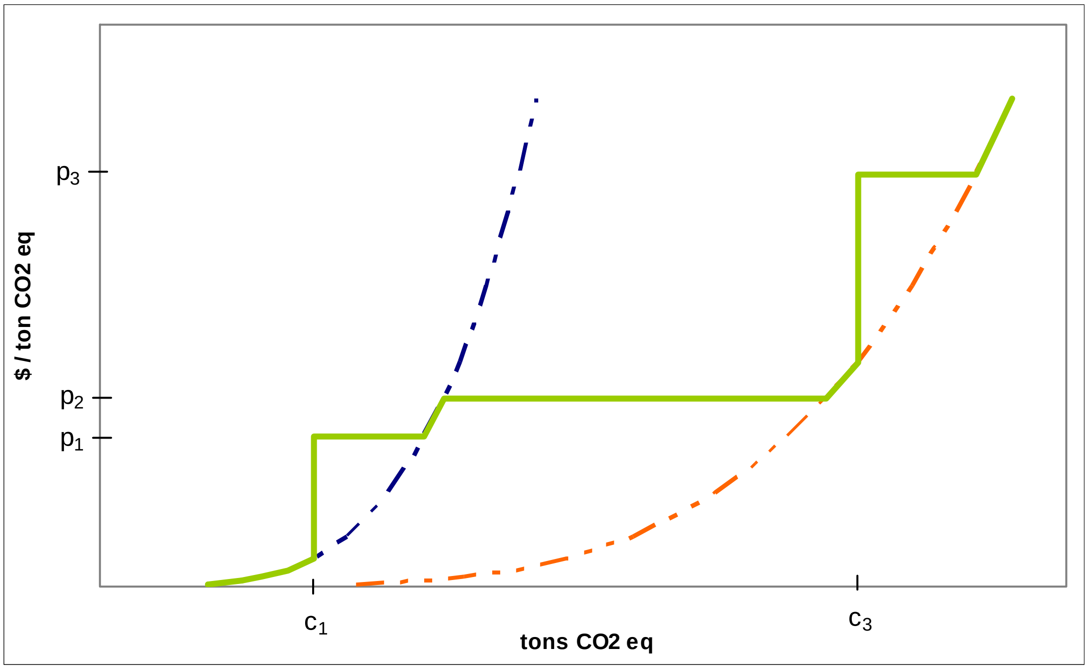
Allowance Offsets for Carbon

The most important greenhouse gas that is a byproduct of electricity generation is CO_2. CO_2 emissions from electricity generation accounted for about 41 percent of energy-related greenhouse gas emissions in the United States in 2007 (U.S. EIA 2008). These emissions have been the focal point of greenhouse gas legislative proposals to promote near term emissions reductions, but other techniques for greenhouse gas abatement, often involving various greenhouse gases, are available to other industries. Legislation for controlling CO_2 emissions from the electricity industry often contains provisions for electricity generators to earn CO_2 reduction credits by paying others to abate greenhouse gas accumulation using these other techniques. These credits are known as allowance offsets.

EPA Office of Air and Radiation (U.S. EPA 2005) describes EPA's development of marginal abatement cost curves for greenhouse gas mitigation outside of the electricity sector. Haiku incorporates these data, along with adjustments made to them by the RGGI Staff Working Group, as allowance offsets supply curves. These data are expressed as tons of CO_2-equivalent abatement for prices expressed in dollars per ton of CO_2-equivalent. Haiku can accommodate regulatory provisions that permit allowance offsets to be used for compliance with an allowance cap-and-trade program by permitting electricity generators to purchase offsets from the offset supply curves. This provision yields CO_2 emissions that exceed allowance caps by an amount equal to the number of allowance offsets purchased from outside the electricity industry.

Proposed RGGI regulation allows carbon offsets to be used up to limits that increase as the allowance price rises. These limits tend to increase the cost of CO_2 allowance offsets and therefore the overall cost of CO_2 reductions. RGGI also expands the geographic area from which allowance offsets can be purchased as the allowance price rises, thereby expanding the potential supply of offsets. Haiku is capable of modeling both types of provisions. Figure 5 illustrates the effects of these policies on the CO_2 offsets supply curve. The dashed function to the left represents the supply curve for CO_2 allowance offsets for a single, small geographic region. The dashed function to the right represents the aggregate supply curve for a larger geographic region that contains the original smaller region. The solid function represents the supply of CO_2 allowance offsets for the smaller region under a regulatory regime in which 1) offsets are capped at c_1 until the allowance price reaches p_1, 2) the smaller region is permitted to buy offsets from its neighbors only after the allowance price reaches p_2, and 3) offsets are capped at c_3 until the allowance price reaches p_3.

Figure 5. CO_2 Allowance Offsets Supply Curve



Policies for Renewable Technologies

Many policies are in place to promote technologies for electricity generation from renewable sources. In addition to direct mandates for investment in renewables in regulated regions of the country, legislatures have adopted renewable portfolio standards, production tax credits, investment tax credits, and performance standards as policy mechanisms to bring renewables online. All of these types of policies can be implemented within Haiku. They are described in the sections that follow.

Renewable Portfolio Standard

A renewable portfolio standard (RPS) imposes a requirement that a minimum percentage of annual electricity generation must be provided by renewable sources. Haiku models an RPS as an allowance trading program in which one renewable energy credit (REC) is equivalent to one MWh of renewable generation, and each generator receives one REC for each MWh generated by a renewable source. A source that is partly renewable (e.g., biomass cofiring) receives RECs commensurate with the percentage of the generator that is powered by a renewable source. The RECs can be traded among facilities and between utilities and this trading is independent of physical power flows. At the end of each year every facility must have enough RECs to satisfy the RPS. For example, if the RPS requires that five percent of national annual generation be renewable, then a utility that generates 1,000 MWh in a year must have possession of 50 RECs. The RPS can be specified at the national level and at the regional level.

Haiku calculates the value of RECs such that the prescribed RPS percentage is achieved. The subsidy value (for renewable sources) or cost (for nonrenewable sources) of the RECs is added to the marginal cost at which generators are dispatched. The model user is able to cap the value of the RECs using the RPS safety valve. In this case, if the REC price reaches the safety valve price, it is not allowed to climb any further and the RPS percentage specified by the user will not be achieved.

Renewable Energy Production Tax Credit

A renewable energy production tax credit (REPTC) is a program under which electricity generators certified as renewable technologies earn a tax credit for generating power. Such programs are already in existence at the federal level and in some states. Haiku models a REPTC by treating it as variable revenue that offsets the variable cost of generation. This moves qualified renewable technologies up in the dispatch ordering of electricity generators and effectively reduces their operating costs. The REPTC can be specified at the national level and at the regional level.

Usually REPTC programs provide the tax credit only to new facilities and only for a fixed duration. Also, these programs are often enacted for only a few years, after which they expire, and may be renewed. For example, the federal REPTC provides a tax credit for renewable generation technologies during their first 10 years of operation, but it has repeatedly lapsed before being quickly renewed. The duration and intermittency of REPTC programs presents a modeling challenge in Haiku because model plants representing new generators are not distinguished by vintage. The problem is managed by treating the REPTC as an infinite stream of tax credits that is identical for all generator vintages within a model plant and equivalent to the present discounted value of the tax credit stream that would accrue to new vintages over a finite horizon. Equation (5) defines *R*, the REPTC value that is used in Haiku. Note that REPTC programs provide a production tax credit, not a production subsidy. A policy that worked as a production subsidy would omit the 1-*t* term from Equation (5).

$$R = \frac{\overline{R}}{1-t}\left[1-\left(\frac{1}{1+r}\right)^{d}\right]p \tag{5}$$

where,

R = value of REPTC expressed as an infinite stream [\$/MWh],

$\overline{R}$ = value of REPTC collectible for *d* years after generator construction [\$/MWh],

t = marginal profit tax rate [dimensionless],

r = discount rate [dimensionless],

d = duration of REPTC eligibility after generator construction [yrs],

p = probability that REPTC will be renewed after expiration [dimensionless].

Technology Performance Standards (NSPS and MACT)

A technology performance standard for emissions requires that specific emissions reduction targets be achieved. New source performance standards (NSPS) for various pollutants are one such example. This standard requires that emissions at newly constructed facilities fall below levels consistent with a maximum emissions rate target. In practice, this translates into specific technologies that become the industry standard. In Haiku, all new investments conform to NSPS.

Another type of technology standard applies to existing as well as new facilities. The maximum achievable control technology (MACT) standard that has been adopted in many states for mercury emissions is one such standard. The MACT as modeled in Haiku may require a specific technology or it can be flexible in requiring that all coal-fired model plants either reduce emissions by a specified percentage or achieve a prescribed emissions rate, whichever is less expensive. See Chapter 3 for details of the implementation of technology performance standards in Haiku.

3. Model Components

Electricity Demand

Haiku classifies electricity demand by three customer classes (residential, commercial, industrial), three seasons (summer, winter, spring/fall), and four time blocks (baseload, shoulder, peak, superpeak). A two-tiered algorithm is employed to project time-block level electricity consumption for each customer class based on retail electricity prices and a set of covariates. At the top tier is a demand system that captures the dynamics of electricity demand in the short- and long-runs to project season level electricity consumption over the simulation horizon. To account for changes in electricity consumption within a season across time blocks when prices are not constant across time blocks, the model incorporates a lower tier system that projects time block shares of seasonal consumption based on the assumption of a constant elasticity of substitution (CES) between consumption in different time blocks of the same season.

The demand system is benchmarked to the electricity consumption projections of the NEMS model, which is maintained by the EIA, as updated annually in the AEO. The benchmarking is performed to derive a set of coefficients that are included in the Haiku demand system that lead to an equilibrium solution in which retail electricity prices equivalent to those in the AEO reference case projections yield electricity consumption that is also equivalent to the AEO reference case projections. This benchmarking yields coefficients that define the levels of the top tier of the Haiku demand system without affecting the price elasticities that are built into the model. Subsequent Haiku model solutions maintain these fixed benchmark coefficients along with the built-in elasticities to project deviations from the benchmark level.

The Haiku system for modeling electricity demand allows for an endogenous top-down approach to capturing improvement in the efficiency of end-use consumption of electricity. The mechanism employed is called the Demand Conservation Incentive (DCI) and it represents a payment to consumers for avoided electricity consumption. This algorithm is an abstraction of the types of policies that exist today and are discussed for implementation in the future, in which financial incentives are provided to electricity consumers for improvements in consumption efficiency.

A Partial Adjustment Demand Model

The partial adjustment demand system finds seasonal electricity demand by customer class given a sequence of electricity prices and other covariates. The model is dynamic due to the electricity price at any time t_0 being a determinant of demand at all subsequent times $t > t_0$. This demand specification is adapted from that advanced by Houthakker and Taylor (1970) as an econometric model for simultaneously measuring the short- and long-run price elasticities of energy demand. In Haiku, this system is used to estimate the elasticities and then to project demand using the parameterized functions and endogenous electricity prices.

$$\begin{gathered} Q^*_{i,t} = \alpha_{i,t} P_{i,t}^{\varepsilon L_i} X_{i,t}^{\beta_i} \\ \left(\frac{Q_{i,t}^{\;2}}{Q_{i,t-1} Q_{i,t-12}} \right) = \left(\frac{Q^*_{i,t}}{Q_{i,t-1}} \right)^{\theta_1} \left(\frac{Q^*_{i,t}}{Q_{i,t-12}} \right)^{\theta_{12}} \end{gathered} \tag{6}$$

$$\ln Q_{i,t} = \frac{(1-\theta_1)}{2} \ln Q_{i,t-1} + \frac{(1-\theta_{12})}{2} \ln Q_{i,t-12} + \frac{(\theta_1+\theta_{12})}{2} \left(\varepsilon L_i \ln P_{i,t} + \beta_i \ln X_{i,t} \right) \tag{7}$$

$$\varepsilon S_i = \frac{(\theta_1+\theta_{12})}{2} \varepsilon L_i \tag{8}$$

where,

$Q^*_{i,t}$ = desired electricity consumption in state *i* at time *t* [MWh],
$\alpha_{i,t}$ = benchmark parameter in state *i* at time *t* [dimensionless],
$P_{i,t}$ = retail electricity price in state *i* at time *t* [\$/MWh],
εL_i = long-run price elasticity in state *i* [dimensionless],
$X_{i,t}$ = covariates in state *i* at time *t* [varies],
β_i = covariate parameters in state *i* [dimensionless],
$Q_{i,t}$ = electricity consumption in state *i* at time *t* [MWh],
θ_1 = partial adjustment parameter for one-month lagged demand [dimensionless]
θ_{12} = partial adjustment parameter for twelve-month lagged demand [dimensionless]
εS_i = short-run price elasticity in state *i* [dimensionless],

Equation (6) describes the theoretical form of the demand functions that are implemented in Haiku, separately for each customer class. Desired demand is equivalent to long-run demand, the level of consumption chosen by consumers who are not capital constrained. By combining the two functions of equation (6) on $Q^*_{i,t}$ and dropping the α term, equation (7) is derived. The coefficients of equation (7) are econometrically estimated using state-level data with a monthly frequency. A fixed effects specification on states is assumed with each coefficient interacted with a dummy variable on the Census Division location of each state and on the season of each month. The estimated coefficients on the price term are the short-run price elasticities of electricity demand for each region and season (and customer class) and the theta terms are calculable from the estimated coefficients on the lagged consumption terms. Hence long-run elasticities are as shown in equation (8). The derivation of the benchmark coefficients, the $\alpha'_{i,t}$ terms, proceeds as described above by reconfiguring equation (7) into the form of equation (9) and using the estimated coefficients εS_i, θ_1, θ_{12}, and β_i . This provides the fully parameterized versions of the electricity demand functions that are implemented as the top tier of the Haiku demand system.

$$Q_{i,t} = \alpha'_{i,t} P_{i,t}^{\varepsilon S_i} \sqrt{Q_{i,t-1}^{(1-\theta_1)} Q_{i,t-12}^{(1-\theta_{12})} X_{i,t}^{\beta_i(\theta_1+\theta_{12})}} \tag{9}$$

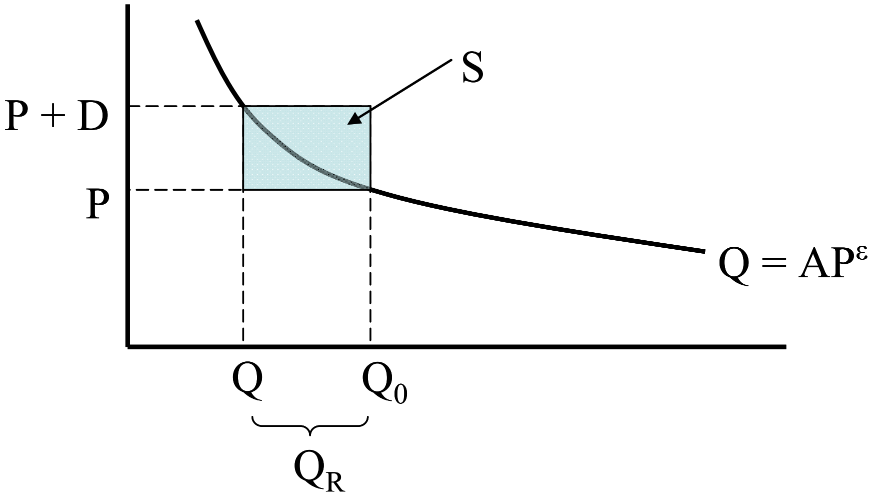
Demand Conservation Incentive (DCI)

An issue in market-based approaches to environmental regulation, such as the use of tradable emissions allowances, is how the allowances are allocated to facilities or, alternatively, how the publicly owned auction or tax revenue is utilized. Some portion of such funds could be allocated to specific purposes to provide special incentives. The Demand Conservation Incentive (DCI) in Haiku provides for the allocation of allowance revenue to consumers in the form of a subsidy to demand reductions brought about by investment in energy efficient end-use electricity consuming capital. The DCI module returns the amount of electricity saved per annum (MWh/yr) based on an annual stream of funding ($/yr) and on the partial adjustment demand functions. In equilibrium, the presence of a DCI program lowers electricity consumption and retail electricity prices.

The core concept of the DCI algorithm is indifference between consumption and non-consumption of the marginal unit of electricity for the marginal electricity consumer. This consumer is willing to forgo consumption of the marginal unit for an infinitesimal payment. When a DCI program is administered to achieve maximal demand reductions given a fixed budget by providing incentives to consumers to reduce electricity consumption, the first unit of consumption avoided will optimally start by buying out the marginal consumer for a price of $0. The infra-marginal consumers require payment greater than $0 and demand increasingly greater payment as the regulator moves farther to the left of the margin. This defines a supply curve for demand conservation that is convex and can be used to estimate demand reductions as a function of total funding for the DCI. The parallel implementation of the DCI algorithm and the partial adjustment demand system allows for the initial reductions garnered under the DCI to persist and abate according to the theta parameters in the demand system.

The essence of the calculation of the DCI is illustrated in Figure 6. In the absence of a DCI, the equilibrium price of electricity is P with quantity demanded of Q_0. The DCI payment per MWh saved is the amount of money that one would have to pay the marginal consumer (post-DCI implementation) to make him indifferent between consuming the last unit of electricity and not doing so, illustrated by the amount D in the graph. Under the assumption that all consumers have to receive the same payment per MWh of electricity consumption reduced, the total amount of money that would be required to obtain Q_R reductions in demand is equal to the DCI price (D \$/MWh) times the quantity of electricity consumption reductions (Q_R), which is shown in the graph as the area S.

Figure 6. Simple Demand Conservation Incentive



Several factors constrain the administrator in implementing a DCI-type program. These include the cost of program administration, the efficiency funds that are captured by free riders (those who would have made the efficiency enhancing investment without the program), and the portion of the retail electricity market that is inaccessible to the administrator. These are captured in Haiku according to equation (10). These functions show the amount of demand reductions delivered by consumers for a DCI of D \$/MWh, given a simplified electricity demand function and an achievable fraction of demand reductions (the percent of potential reductions that the regulator is able to obtain through the program). The amount of money that the program administrator must spend to achieve these reductions is given by the formula for S that incorporates the effects of having to spend some of the money on administrative costs, which don't go to consumers, and being unable to distinguish free riders from other program participants.

$$Q_0 = AP^{\varepsilon},\ Q_R = Q_0\left[1-\left(1+\frac{D}{P}\right)^{\varepsilon}\right]Ach,\ S = \frac{DQ_R}{(1-FR)(1-Admin)} \tag{10}$$

where,

Q_0 = electricity demand in the absence of DCI [MWh],
A = electricity demand covariates except for electricity price [varies],
P = retail electricity price [$/MWh],
ε = short-run price elasticity [dimensionless],
Q_R = demand reductions achieved by DCI [MWh],
D = DCI payment [$/MWh],
Ach = achievable percentage of economic reductions [dimensionless],
S = government spending on efficiency program [$],
FR = free-rider rate [dimensionless],
$Admin$ = administrative cost rate[dimensionless].

Capacity Investment and Retirement

The generation capacity investment and retirement algorithms in Haiku assume perfect foresight. The model finds simultaneous equilibria that are inter-temporally consistent, with capacity decisions in all years consistent with equilibrium solutions for all control variables in all other years. Inter-temporal consistency for capacity applies both to physical capacity bounds and economic constraints. Because Haiku aggregates generation capacity into model plants, the capacity algorithms work at the marginal MW of each model plant and make continuous adjustments to capacity. For more discussion on the nature of model plants and for an overview of the convergence techniques employed by Haiku, see Chapter 0.

Cost Accounting

The key variable in the capacity algorithm is going-forward profits. Going-forward profits in any year are all revenues earned by a generator less costs that would have been avoided if the generator were retired or not constructed. For new capacity investment, going-forward profits are all revenues less all costs, including variable and fuel costs, fixed costs for maintenance and administration, and capital costs. For retirement of preexisting capacity, going-forward profits are all revenues less all costs except capital costs. Capital costs are not included in going-forward profits for preexisting capacity because they are sunk and therefore unavoidable. For investment in new capacity to be economic, it must have positive going-forward profit in the current year and the net present value of all future going-forward profits must also be positive. For pre-existing capacity to retire, it must have negative going-forward profits in the current year and the net present value of all future going-forward profits must also be negative. The components of going-forward profit are detailed in Table 4.

Table 4. Going-Forward Profits: Components and Inclusion Status by Capacity Vintage

	Capacity Vintage	
Revenues	Existing	New
Generation	X	X
Reserve services	X	X
Stranded cost recovery	X	X
Costs		
Variable costs for dispatch[1]	X	X
Fixed operation and maintenance	X	X
General and administrative	X	X
Taxes	X	X
Capital cost for generation capacity		X
Capital cost for endogenous pollution controls	X	X
Cost of displaced existing capital[2]		X
Imported power	X	X

1. For a detailed accounting of variable costs for dispatch, see the section below on Production.
2. Applies only in regions with regulated electricity pricing.

Revenues from generation and reserve services are calculated based on the generation price and reserve price (these are discussed below in the section on Production). Generation price, which is equivalent to the marginal cost of generation, is paid to every MWh of generation. The reserve price reflects the scarcity value of capacity and is set just high enough to retain just enough capacity to cover the required reserve margin in each time block. The reserve price is paid to every MW of reserve service and generation. Generation receives the reserve price because it not only contributes to demand for electricity, but also reduces the scarcity of capacity. If generation did not receive the reserve payment there would be an incentive compatibility problem in the superpeak time blocks, with marginal generators preferring to withhold power from the electricity generation market in order to participate in the capacity market. Paying the reserve price to plants that actually generate removes this incentive incompatibility and properly values the capacity contribution of electricity generation.

Haiku amortizes all capital costs. The capital recovery factor is the coefficient that describes the fraction of up-front capital costs that an electric utility bears annually. The capital recovery factor for investment in pollution controls is exogenous to the model and assumed uniform for all types of pollution control. The capital recovery factor for investments in generation capacity depend on an algorithm that accounts for the time required to construct new generation capacity and the economic lifetime of such investments. These parameters vary across different types of generation capacity. The algorithm also depends on the real cost of capital, which is assumed to be uniform across the electricity industry.

Capacity Bounds

The generation capacity of each model plant is bounded above and below in each simulation year. For existing generators, the lower bound on capacity is always zero; that is, any existing capacity may retire at any time if it meets the economic conditions for retirement.[8] The upper bound on existing capacity in the first simulation year is simply the quantity of existing capacity. In subsequent simulation years, the upper bound is equal to the amount of capacity which is not retired in the previous year. Thus existing capacity can retire completely, but may not be rebuilt once it is retired. For new investments, Haiku accounts for both capacity that is under construction or planned for construction in the data year, and for endogenous investment in new capacity. New capacity is never permitted to retire once it is constructed. Therefore, new capacity which is already under construction or planned in the data year defines the lower bound for new capacity in the first simulation year. In subsequent years, the lower bound for new capacity is equal to the amount of new capacity constructed in the previous simulation year. The upper bound for new capacity investments of each technology type is an annual rate that is defined relative to the total capacity in each region in the data initialization year. This parameter is defined by the model user.

Haiku may be configured to simulate a "policy surprise." In this configuration, a baseline model is solved using the constraints described above. Then a policy model is constructed that contains some policy, like new environmental regulation, that was absent in the baseline run and

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[8] Hydroelectric generation capacity, both conventional and pumped storage, is not permitted to retire or construct new capacity.

a specified time at which the new policy is announced. To solve the policy model Haiku looks to the solution of the baseline model for capacity retirement and investment in the years prior to the announcement of the new policy. This baseline level of capacity is treated by the policy model as existing capacity in the policy announcement year. From this year forward the standard algorithm described above is used to determine capacity investment and retirement.

Technological Learning

For new types of electricity generation technology, such as integrated gasification combined cycle (IGCC) plants, it is expected that as more plants are constructed their capital costs will fall. This phenomenon is called learning by doing. Haiku employs the model used by the EIA (2006) to simulate technological improvement in new electricity generation capacity. The essence of the model is that the component parts of any new generation capacity will become cheaper as more are built. The rates at which capital costs fall depend on the maturity of the technology; as the technology matures, the rate of improvement declines. Because different types of generation capacity share mutual components, the construction of any type of capacity will contribute to the improvement of other types of capacity via those mutual components. For example, both IGCC plants and combined cycle plants incorporate a heat recovery steam generator. When either type of plant is constructed, the learning achieved about the heat recovery steam generator technology will lower the capital cost of future construction of either type of plant.

Availability

The fundamental unit of generation capacity in the Haiku model is nameplate capacity. The potential for electricity generation of one MW of nameplate capacity varies through time as ambient conditions change, the plant is taken offline for maintenance, and unscheduled outages occur. Haiku accounts for adjustments to nameplate capacity due to ambient conditions using historical data, from which a ratio between nameplate capacity and operating capacity is calculated for each model plant and season. An endogenous algorithm for determining the timing of scheduled maintenance is described in the next paragraph. Unscheduled outages are assumed to occur with equal frequency during periods for which a generator is scheduled to be in operation. Equation (11) defines the relationship between nameplate capacity and potential electricity generation in each season.

$$PG_{ijk} = N_k r_{jk} \left(1 - s_{jk}\right)\left(1 - u_k\right) H_i \tag{11}$$

where,

PG_{ijk} = potential generation in time block *i* of season *j* for model plant *k* [MWh],

N_k = nameplate capacity of model plant *k* [MW],

r_{jk} = ratio of operating capacity to nameplate capacity in season *j* for model plant *k* [dimensionless],

s_{jk} = fraction of season *j* devoted to scheduled maintenance for model plant *k* [dimensionless],

u_k = probability of unscheduled outage for model plant *k* [dimensionless],

H_i = number of hours in time block *i* [hrs].

Each model plant in Haiku has a specified scheduled outage rate—the fraction of hours the plant is down annually for scheduled maintenance. Because Haiku is a seasonal model, the scheduled outage rate needs to be expressed by season, but the opportunity cost of a scheduled outage (electricity price) is not the same for all seasons. Generators tend to allocate more scheduled outages to low-price seasons and fewer scheduled outages to high-price seasons. Haiku endogenously allocates scheduled outages to the three seasons according to the average seasonal electricity price, both when it is determined by regulation and when it is determined by marginal cost.

The availability of some types of capacity is not modeled in the manner described above. These include hydroelectric turbines, both conventional and pumped storage turbines, and wind turbines. Seasonal generation by conventional hydroelectric turbines is constrained not by the capacity of the turbines, but by the amount of water available. Haiku looks to historical data for seasonal hydro generation, and then endogenously allocates this generation to the time blocks in which it is most valuable, bounded above by the capacity of the turbines and bounded below by the run-of-the-river requirement. Generation by hydroelectric pumped storage capacity is not permitted during base time blocks, as this is the time when water is collected for use in more valuable time blocks. The time block specific capacity factor of wind turbines in Haiku is defined exogenously in the model.

Production

Haiku models the requirement for electricity generation and reserve services in each time block depending on electricity demand, the reserve margin requirement, interregional power trading, and losses in interregional and intraregional transmission and distribution. Equations (12) and (13) define these relationships.

$$G_{ij} = \frac{D_{ij}}{\left(1-a\right)} + E_{ij} - \sum_{k} I_{ijk}\left(1-e_{jk}\right) \tag{12}$$

$$R_{ij} = \frac{D_{ij} m_j}{H_i} \tag{13}$$

where,

G_{ij} = requirement for generation in time block i in region j [MWh],
D_{ij} = electricity demand in time block i in region j [MWh],
a = coefficient for intraregional transmission and distribution losses ($0<a<1$) [dimensionless],
E_{ij} = total power exports in time block i from region j to contiguous regions [MWh],
I_{ijk} = power imports in time block i to region j from region k [MWh],
e_{jk} = coefficient for interregional transmission losses between regions j and k ($0< e_{jk} <1$) [dimensionless],
R_{ij} = requirement for reserve services in time block i in region j [MW],
m_j = reserve margin requirement in region j ($0< m_j <1$) [dimensionless],
H_i = number of hours in time block i [hrs].

Demand for generation and reserve services are satisfied in Haiku for each time block using two separate supply curves. First, electricity generators are dispatched according to their variable costs to meet the requirement for generation. Then the remaining capacity that is not used for generation is dispatched according to unrecovered going-forward fixed costs to meet the requirement for reserve services. The remainder of this section will describe these supply curves.

Generation

The requirement for electricity generation in Haiku is met using generation supply curves that are distinct for each region and time block. The model plants with available potential generation in each region and time block are dispatched according to their variable costs. Equation (14) shows the components of variable cost that are accounted for in generation dispatch. Each model plant has a unique value for V_{ij}.

$$V_{ij} = v_j + f_j + \sum_{l}\left(\theta_{jl} p_{jl} - \alpha_{jl}\right) + \rho_1 + \rho_2 + c_k \tag{14}$$

where,

V_{ij} = variable cost for generation dispatch in time block i of season j [\$/MWh],
v_j = variable cost of operation and maintenance[1] in season j [\$/MWh],
f_j = fuel cost in season j [\$/MWh],

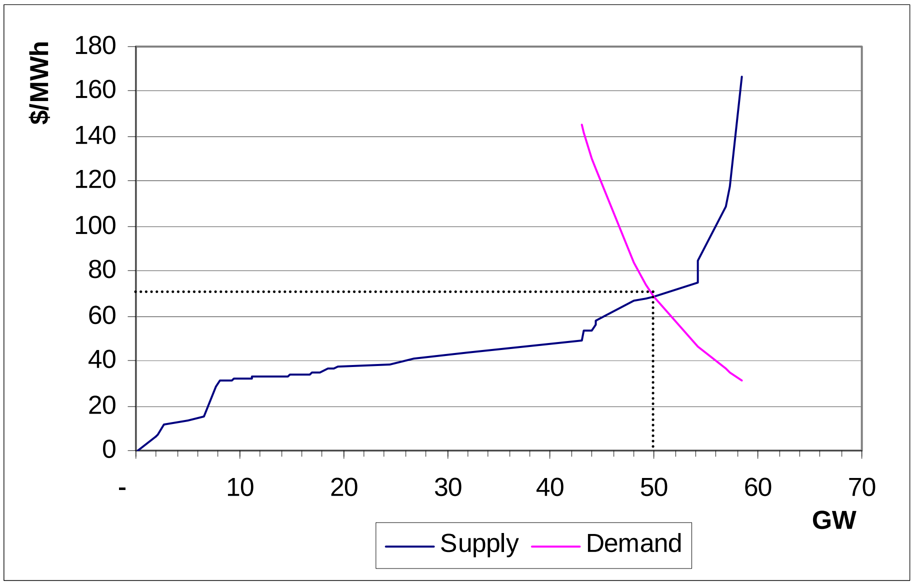
θ_{jl} = emission rate in season j for pollutant l [tons/MWh],
p_{jl} = aggregate price for allowances or taxes assessed on pollutant l in season j [\$/ton],
α_{jl} = allowance subsidy[2] for generation in season j for pollutant l [\$/MWh],
ρ_1 = renewable energy production credit [\$/MWh],
ρ_2 = value of renewable portfolio standard allowance [\$/MWh],
c_k = generation calibrator[3] for model plant k [\$/MWh].

1. Includes variable cost of operation and maintenance for installed post-combustion pollution controls.
2. This subsidy is realized when allowances are allocated under updating-based allocation.
3. Applies only for steam generators powered by natural gas or oil. See the section below on Calibration in Chapter 3.

To facilitate model convergence and better represent the heterogeneity of the constituent generators that comprise a model plant, Haiku dispatches model plants assuming that each has a uniform distribution of variable costs around a mean of V_i. The lowest variable cost model plants are dispatched first with each model plant providing generation not exceeding its potential generation. Haiku reads up the supply curve until the generation requirement in each time block is satisfied. This implies the amount of generation performed by each model plant and a marginal cost of generation in each time block. The generation price in each time block, which is a component of electricity price, is set equal to the marginal cost of generation. Figure 7 is an example of a generation supply curve and illustrates the calculation of marginal generation cost and generation price. In the figure, 50 GW is the equilibrium level of supply and demand and the generation price is \$70/MWh. The electricity pricing algorithms employed in Haiku were discussed in detail in Chapter 2.

Some of the model plants are not dispatched in the manner described above. Biomass cofiring is a generation option chosen by some coal boilers and if cofiring is adopted, the portion of the model plant capacity that is using biomass fuel is automatically dispatched with the rest of the coal boiler. The costs of the coal boiler are adjusted for the biomass cofiring portion. Hydroelectric pumped storage capacity is also dispatched in a special way. It is assumed that any generation performed by pumped storage is the result of electricity consumption in the base time block to prepare the water for generation in higher value time blocks. The amount of generation is determined according to the efficiency of the pumps and the time block specific electricity prices relative to the electricity price for industrial customers in the base time block.

Figure 7. Illustration of Generation Supply Curve



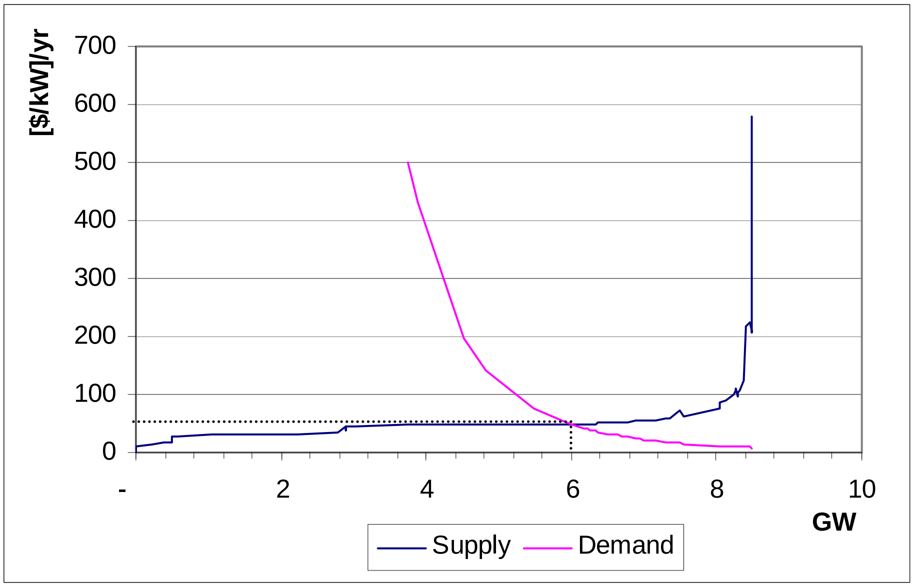
Reserve Services

The supply curves for reserve services are constructed based on unrecovered going-forward fixed costs that include all fixed costs that would be avoided if the model plant were retired or not constructed less surplus earned in all time blocks in the electricity generation market. Because each component MW of each model plant need not earn identical surplus in the generation markets, the model plants are disaggregated into sets of component MWs with identical unrecovered going-forward fixed costs. All of these sets of component MW are called sub-model plants and are used only for dispatching capacity to meet reserve requirements.

The potential generation of each sub-MP in each time block is reduced by the amount of generation performed by that sub-MP in the electricity generation markets. The resulting value (in MWh) is divided by the duration of the time block to find the potential for each sub-MP to provide reserve services (in MW). The dispatch ordering for reserve services is determined by the unrecovered going-forward fixed costs of each sub-MP. As discussed above in the Capacity Investment and Retirement section, the fixed costs that count as going-forward depend on the vintage of the model plant. See Table 4 for an accounting of the going-forward costs.

Haiku does not model separate markets for spinning reserves and capacity reserves. Instead, the fraction of reserve services provided by steam generators is constrained to be no greater than 50 percent of the total reserve requirement in each time block. Given this constraint, Haiku constructs supply curves for reserve services using the aforementioned sub-MPs ordering and quantity of potential reserve for each sub-MP. The model reads up the supply curve to the prescribed reserve requirement for each time block to find the quantity of reserve services provided by each sub-MP and model plant. Figure 8 is an example of a supply curve for reserve services.

Figure 8. Illustration of a Supply Curve for Reserve Services



Interregional Power Trading

Haiku employs a reduced form interregional power trading model in which the national transmission grid is represented as a set of potential bilateral trades between every pair of contiguous regions. For regional pairs that are not contiguous, no direct power trading is allowed. However, power trades between noncontiguous regions may be executed through intervening regions that connect the noncontiguous regions. The model accounts for differences in regional electricity prices, interregional line losses, and transmission costs in a pancake manner to find equilibria subject to constraints on interregional transmission capability. Pancaking means that fees and losses for interregional power trades are assessed at each regional boundary such that they accumulate for power that is traded between noncontiguous regions. Each time block has a unique equilibrium.

The heart of the interregional power trading algorithm in Haiku is the equilibration across regional boundaries of willingness to pay for power, subject to the assumed level of available interregional transmission capability. The equilibration is net of interregional transmission losses and fees. In practice, the transmission capability constraints are often binding, leaving sometimes significant differences between willingness to pay in contiguous regions. The model allows only for exogenous growth over time in interregional transmission capacity, with the annual growth rate in capacity to be specified by the model user. The default growth rate assumption is one percent per year. The costs of transmission expansion are not modeled in detail and are assumed to be recovered in the interregional transmission fee, which is assessed per MWh of power transmitted between regions.

Two types of trades are modeled. Economy trades are the type described above. Firm trades represent prearranged commitments to provide power over the interregional transmission system. Exogenous estimates of firm trades come from historical data and EIA projections. These include both estimates and trading quantity and price.

Economy trades are calculated based on the willingness to pay for interregionally traded power. Willingness to pay is defined as the sum of generation price and reserve price (see the section on Competitive Pricing in Chapter 2 for a discussion of these prices). Reserve price is a component of willingness to pay because imported power reduces demand not just for electricity generation, but also for scarce capacity as generators displaced from the generation market are able to contribute capacity to the reserve margin and lower the scarcity value of capacity. Economy trades are priced at the mean of the willingness to pay—net of interregional losses and fees—in the two regions trading. When the capability for transmitting power is not binding, these two values are equal. Equation (15) defines the price for an economy trade between any importing region *I* and contiguous exporting region *E*.

$$P_{IE} = \frac{1}{2}\left(W_I + \frac{W_E + c_{IE}}{l_{IE}} \right) \tag{15}$$

where,

P_{IE} = price for interregional economy trades between importing region *I* and exporting region *E* [\$/MWh],

W_I = willingness to pay for power in region *I* [\$/MWh],

W_E = willingness to pay for power in region *E* [\$/MWh],

c_{IE} = interregional transmission cost between regions *I* and *E* [\$/MWh],

l_{IE} = interregional transmission losses between regions *I* and *E* ($0<l_{IE}<1$) [dimensionless],

Canada is treated in the model as an aggregate entity with which limited power trading is permissible. Potential trades with Canada exist for many of the northern regions in Haiku. Since the model does not include a representation of the Canadian electricity system, exogenous projections of international power trading quantities and prices are used to constrain such trades. Given these quantity constraints and prices, Haiku endogenously determines these trades. There is no power trading with Mexico represented in the model.

Pollution Controls

Haiku models post-combustion pollution abatement technologies for three different pollutants: NO_x, SO_2, and mercury. The model chooses a set of abatement technologies for each relevant model plant and the variety of coal that is burned at coal-fired steam model plants. Because coal choice and some types of abatement technologies have effects on the emission rates of multiple pollutants, the Haiku pollution control algorithm is integrated to consider all pollutants, including CO_2, simultaneously. The algorithm is also integrated over all simulation years to yield a solution that is intertemporally consistent and optimal over the modeling horizon.

The types of pollution abatement technologies considered by the model are selective catalytic reduction (SCR), flue gas desulfurization (FGD) in both wet and dry configurations, and activated carbon injection (ACI). These technologies may be installed in combinations for which the economics depend on the cost of emissions of each type of pollutant and the capacity factor of the model plant on which they are to be installed. The combinations of pollution abatement technologies considered in Haiku are enumerated in Table 5. Not all combinations of pollution abatement technologies are practical or legal for all model plants. For example, investment in new coal boilers is assumed to include construction of SCR and wet FGD. Other abatement technologies are forbidden. Columns two through five in Table 5 detail which combinations of pollution abatement technology are permissible for each type of model plant.

Each combination of pollution abatement technologies has a unique set of abatement coefficients for each pollutant. The cost parameters for each technology are also unique, including estimates of variable operations and maintenance (O&M), fixed O&M, and capital cost. Haiku permits coal-fired steam boilers to select a coal type from a set of fourteen types derived from data compiled by the EIA. Each of these fourteen coal types has unique values for heat content and pollutant contents for SO_2, CO_2, and mercury. Each coal type also has a unique price for each model plant that is derived from the coal supply curves described in the section below called Fuel Market and Natural Resource Supply Modules. Haiku assumes that coal boilers may switch coal types costlessly.

Table 5. Pollution Abatement Technologies and Their Applicability to Model Plants

Abatement Technology	New Steam Coal	Existing Steam Coal[1]	New IGCC Coal	Existing Steam Gas / Oil
None		X		X
SCR		X	X	X
Wet FGD		X		
Dry FGD		X		
ACI		X		
Wet FGD & ACI		X		
Dry FGD & ACI		X		
SCR & wet FGD	X	X		
SCR & dry FGD		X		
SCR & ACI		X	X	
SCR & wet FGD & ACI		X		

1. Most existing coal-fired steam boilers already have some combination of pollution abatement technologies. Haiku assumes that these will not be replaced, thus shortening the list of technologies that may be endogenously constructed.

The Haiku pollution control algorithm minimizes the present discounted value of compliance costs over the modeling horizon assuming that any pollution abatement technology that is constructed will never be removed. To achieve this intertemporally consistent solution, the set of abatement technologies given in Table 5 is concatenated over model simulation years to yield one superset of competing compliance strategies that consists of the timing of abatement technology investments and, for coal-burning model plants, a coal choice in each year. For each model plant, the optimal strategy from this superset is selected. Given an equilibrium pattern of electricity generation over time, equilibrium allowance prices or pollutant taxes, and the cost and performance parameters of each combination of pollution abatement technology and coal type, Haiku chooses the set of compliance measures that satisfy equation (16). For model plants that burn natural gas or oil, the coal choice component of equation (16) is omitted.

$$\underset{i\in I,j\in J}{\arg\min}\sum_t\left(\frac{1}{1+r}\right)^t\Bigg[K_{it}+F_{it}+g_t\left(V_i+C_{jt}h_t+\sum_k P_{kt}e_{ijkt}\right) \quad (16)$$

where,
I = set of pollution abatement investment strategies including investment timing,
J = set of coal types,
r = discount rate [dimensionless],
t = time [yrs],
K_{it} = annualized capital cost for strategy *i* at time *t* [\$/yr],
F_{it} = fixed O&M for strategy *i* at time *t* [\$/yr],
g_t = electricity generation at time *t* [MWh/yr],
V_i = variable O&M for strategy *i* [\$/MWh],
C_{jt} = price of coal type *j* at time *t* [\$/kBtu],
h_t = heatrate at time *t* [Btu/kWh],
P_{kt} = allowance price or tax rate for pollutant *k* at time *t* [\$/ton],
e_{ijkt} = emission rate of pollutant *k* at time *t* using strategy *i* and coal type *j* [tons/MWh],

To model technology performance standards, like NSPS and MACT, Haiku simply omits combinations of abatement technology and coal type which do not comply. Then the standard algorithm for pollution control choice, as described in equation (16), is implemented. For more on the nature of technology performance standards, see Chapter 2.

Fuel Market and Natural Resource Supply Modules

Haiku has reduced-form fuel market modules that endogenously determine prices for coal, natural gas, and biomass. The costs of wind and geothermal resources are represented as supply curves that reflect the increasing cost of those resources as more are taken up. This section describes each of these modules. Prices for oil, nuclear fuel, and landfill gas are specified exogenously and may change over time.

Coal

EIA reports projections of coal consumption by electric utilities and mine mouth coal prices for a set of coal types from a set of coal supply regions. Haiku takes those data and aggregates them to fourteen coal supply categories, each with known heat content and pollutant contents for SO_2, CO_2, and mercury. EIA reports that a 10 percent deviation from the projected coal production will result in a one percent change in projected coal price. EIA also reports a markup (transportation fee) for each combination of coal demand region and coal supply region. With all of this information, Haiku calculates coal supply curves that describe the delivered prices of the fourteen coal types in the thirteen coal demand regions as a function of electric utility demand for each coal type.

Natural Gas

EIA reports projections of natural gas consumption and national average wellhead price for the entire U.S. economy for three cases: low economic growth, reference, and high economic growth. Haiku uses these three data points to derive a linear natural gas supply curve for the entire U.S. economy. EIA also reports the projected natural gas consumption by all sectors of the economy except electric utilities. Using these data, Haiku calculates the national average wellhead price for natural gas based on endogenous natural gas consumption by the electric utility sector and exogenous consumption by all other sectors. Also from EIA data, a natural gas markup (transportation fee) is calculated for each region of the country, allowing Haiku to express the delivered natural gas price as a function of electric utility demand for natural gas.

Biomass

The supply curves for biomass fuels that are suitable for combustion for electricity generation are derived from two studies. The first study (Walsh et al. 2000), completed at the Oak Ridge National Laboratory (ORNL), characterizes supply curves for five types of biomass feedstock: forest residues, mill residues, agricultural residues, urban wood wastes, and dedicated energy crops. These supply curves are specified at the state level. The second study (Milbrandt 2008), completed at the National Renewable Energy Laboratory (NREL), provides production potential in terms of quantity for the same five categories of biomass feedstock. These data are reported at the county level and mapped into two geographic dimensions—state and Haiku market region (HMR)—according to a land area weighting.

Haiku combines the data in these two studies at the HMR level by scaling the ORNL data such that the far right-hand side of the supply curves for each type of biomass feedstock correspond with the maximum production potential reported in the NREL study. The ORNL data are mapped from states into HMRs using the weighting provided by the NREL study mapped into states and HMRs. Thus Haiku calculates biomass supply curves at the HMR level that take the shape of the ORNL study and width of the NREL study. The five types of biomass are aggregated into a single biomass supply curve from which a fuel price can be determined for any level of biomass demand. There is feedback between Haiku modules to find the equilibrium level of biomass demand determined by capacity investment, generator dispatch, and biomass fuel price.

Wind

The wind resource supply curves were derived from data supplied by EIA. A study conducted by Princeton Energy Resources International for EIA (Princeton Energy Resources International 2007) estimated incremental wind capacity availability by wind class, NEMS region, and long term cost multiplier category. The cost multipliers were used to indicate the additional capital costs above the cost of the turbine associated with accessing wind resources in increasingly remote locations and connecting them to the transmission grid. The long term multipliers were created using NREL's GIS optimization model and reflect citing difficulty and interconnection costs associated with different amounts of wind resource within each region. These estimates were then divided into HMRs using the weighted average available capacity by WinDS (Wind Deployment System) region. WinDS is a geographically detailed model of wind generation resources maintained by NREL. Information on wind capacity factors by location comes from inputs to the EIA NEMS model.

Geothermal

The geothermal supply curves were obtained from EIA. EIA updated its data for the 2007 AEO based on data from two studies: WGA (2006) and GeothermEx Inc (2004). The data contains site-specific capacity availability and four categories of capital costs: exploration, confirmation, development, and transmission. This site-specific information was aggregated to the HMRs to construct regional resource supply curves for geothermal electricity generation.

Calibration

There are numerous factors that affect the operation of the electricity system that are not explicitly captured by the Haiku model. These include intraregional transmission constraints, out-of-merit-order dispatch, electricity market price controls, market power, general equilibrium capital market effects, and so on. Two calibration factors in Haiku serve as aggregate correction terms. They are the electricity price calibrator and the variable O&M cost calibrator. These values are such that the model solution for a historic year with verifiable data matches the data for regional average annual retail electricity price and regional annual generation by fuel and technology type (in MWh) for natural gas and oil-fired steam boilers and combustion turbines.

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Acronyms

ACI	Activated carbon injection
AEO	Annual Energy Outlook
CES	Constant elasticity of substitution
DCI	Demand conservation incentive
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FGD	Flue gas desulfurization
IGCC	Integrated gasification combined cycle
HMR	Haiku market region
MACT	Maximum achievable control technology
MP	Model plant
MSW	Municipal solid waste
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
NSPS	New source performance standard
O&M	Operations and maintenance
ORNL	Oak Ridge National Laboratory
PUC	Public utility commission
REC	Renewable energy credit
REPTC	Renewable energy production tax credit
RFF	Resources for the Future
RPS	Renewable portfolio standard
SCR	Selective catalytic reduction
SIP	State implementation plan
T&D	Transmission and distribution

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