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Multi-regional evaluation of the U.S. electricity sector under technology and policy uncertainties: Findings from MARKAL EPA9rUS modeling

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A B S T R A C T

The concern of the environmental impacts of electricity generation from fossil fuels and the desire for the country to be less dependent on fossil fuels have resulted in the U.S. Government offering various incentives to promote electricity from renewable sources. The U.S. electricity generation sector faces uncertainties that include future demand, the costs of supply, and the effects of regulation policies. National policies that aim to promote "clean" energy sources may have different impacts for different areas of the country, so it is important to understand the regional effects in addition to the larger national picture. The primary purpose of this paper is to shed some light on the uncertainties associated with the outcomes of possible regulations.

The study does not intend to make predictions of the probability or direction of environmental policy in the U.S. Rather, we examine a number of different scenarios and explore their possible impacts on the future of energy system. We focus on future projections for electricity generation mix, electricity costs, emissions and emissions abatement costs under different scenarios. We have examined the key regulations through analyzing various assumptions using the MARKet ALlocation (MARKAL) model and the Environmental Protection Agency's Nine Region MARKAL Database (EPAUS9r).

We have analyzed how command-and-control regulations and market-based environmental policy approaches could change the mix of fuels used for electricity generation, the amount of CO_2 emissions, and the cost of electricity in different parts of the U.S. In particular, we explore how some proposed features of different policies designs affect those outcomes and identify underlying causes of uncertainty about such outcomes.

The analyzed policies lead to 6–25% reduction in total CO_2 emissions by 2035. The policies also result in modest increases on electricity costs nationally, but this masks a wide variety of effects across regions. The relationship between the policy's effects on costs depends on the design of the policy, regional resource endowments, and the existing generation mix of the region. Generally, the regions with existing high electricity marginal costs would tend to see only minor costs increases and the regions with low electricity marginal costs would see substantial costs increases. Modeling results illustrate that different regions have different preferences in environmental regulations policies and design.

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1. Introduction

The framework of U.S. energy and GHG emissions regulation policies are still under discussion. Current (Spring 2012) debates about increasing the amount of renewable energy in the U.S. focus on the creation of a Clean Energy Standard (CES). Though the specifics of a CES are still unclear, it is likely that each utility would be required to provide an increasing fraction of their total production from qualified clean energy resources. According to recent studies on air regulations impacts, the estimates of coal plants retirements driven by these regulations range from 6 GW to 65 GW by 2020 (see Refs. [1–7]).

A key concern is that some regions do not have as many cost-effective clean resources available as are required at a reasonable cost. In this case utilities may need to import significant quantities of clean energy from other regions, most likely wind power from the Midwestern states. Other options may be available too, such as higher-cost local generation, or purchase of renewable credits without electricity transmission.

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Thus, the electricity generation sector faces uncertainties that include future demand, the costs of supply, and the effects of potential policies. Many policies could be set not only at the federal level, but also at the state or regional level. Furthermore, federal laws and policies could be created by states representatives that have the interests of their individual states. Therefore, it is important to understand the regional effects in addition to the larger national picture.

Increasing the share of electricity generation from renewables, nuclear or plants with carbon capture and storage (CCS) would reduce CO_2 emissions (compared with what they would be otherwise). However, it would require overcoming a variety of obstacles that generally make renewable and clean generation technologies more costly than conventional fossil fuel generation technologies. Those complications include, but not limited to, the location-specific and variable nature of some renewable energy sources, technological uncertainties, and environmental concerns. Significantly expanding the use of low-emitting sources to generate electricity (through a Renewable Electricity Standards (RES), CES, or other policy) would require addressing those complications.

The primary purpose of this paper is to throw some light on these uncertainties associated with outcome of possible regulations at the regional level. We focus on future electricity mix, electricity generation costs, CO_2, SO_2, NO_x emissions levels and emissions abatement costs under different scenarios assumptions. We have examined a number of potential regulatory regimes through analyzing various scenarios using MARKAL model and EPAUS9r database.

2. Description of the modeling framework

Energy system models are known for their capability to analyze energy and environmental issues and can provide insights on future developments in the energy sector under external constraints. We use the MARKet ALlocation (MARKAL) energy system model [8–10]] that allows different scenarios to be examined quantitatively in a dynamic energy system context. The MARKAL model is a “bottom-up” technology-based linear optimization model. MARKAL, in its standard form, identifies the least-cost combinations of technological processes and improvement options that satisfy a specified level of demand for goods and services under certain policy constraints, notably the achievement of certain specified emissions reduction objectives, carbon taxes, or fuel taxes/subsidies in a way that the overall system costs are minimized over all time periods simultaneously.

MARKAL is a vertically integrated model of the entire energy system. The MARKAL model aims to supply energy services at minimum total cost by simultaneously making investment, operating and primary energy supply decisions. For example, if there is an increase in residential lighting energy service, either existing generation equipment must be used more intensively or new equipment must be installed. The choice of generation equipment (type and fuel) incorporates analysis of both the characteristics of alternative generation technologies and the economics of primary energy supply. MARKAL computes an inter-temporal partial equilibrium on energy markets, which means that the quantities and prices of the various fuels and other commodities are in equilibrium, i.e. their prices and quantities in each time period are such that at those prices the suppliers produce exactly the quantities demanded by the consumers. Investments made at any given period are optimal over the horizon as a whole.

The MARKAL modeling platform provides the ability to perform comparative scenario analysis (NOT necessarily a prediction) and takes into account the following driving forces: technological change, energy demand, energy supply and price dynamics. MARKAL is a data-driven energy systems model that contains resource supplies, energy conversion technologies, end use demands, and the technologies to satisfy these demands, and the data to characterize each of the technologies and resources. Outputs of the model include the energy mix, estimates of total system cost, energy services cost, and GHG emissions estimates.

The model comprises the whole energy chain, from supply resources through conversion and transformation, to distribution to end users (see, e.g., Ref. [11]). The model version used for this paper covers the 2005–2055 period in 5-year steps, with over 500 energy and material demand categories and more than 3000 technologies.

We applied the EPAUS9r database that was developed by Environmental Protection Agency (EPA) around the nine U.S. Census divisions [12]. The primary source for database is the U.S. Department of Energy's Annual Energy Outlook (AEO). Each of the nine (R1–R9) regions has its own conventional Reference Energy System (RES) and these nine RESs are interconnected through trade technologies links. The regions identification is given in Fig. 1.

The Base case energy demand projections are developed for the entire forecast horizon based on exogenous regional economic and demographic projections and assumptions regarding each service demand's is consistent with the Energy Information Administration's Annual Energy Outlook 2010 (AEO 2010) [13]. The model must satisfy these demands in each time period, by using the existing capacity and/or by implementing new capacity for end-use technologies. These demands are set only for the Base case, but are endogenously determined in alternate scenarios where the prices of energy services vary from the Base case prices. For example, a scenario causing the cost of electricity generation to rise relative to the Base case and, ceteris paribus electricity demand would decline relative to the Base case. An increase in the electricity cost relative to the Base case would also affect investment decisions. Over time, as the stock of equipment turns over, more efficient demand technologies may be chosen, tending to lower the cost of service, thus increasing service demand.

EPAUS9r contains both existing and future technologies, so even in a base case scenario, without additional constraints, a shift towards more cost-efficient technologies occurs. A number of conservation options in the end use sectors are included. Energy conservation options become more attractive for the optimal solution in emission control scenarios if the existing or carbon-intensive base case technologies experience a higher penalty (see, e.g., Ref. [14]).

In addition to the nine interconnected regions, there is a supply region R0. For all imports and for each of the nine regions into which an import may flow, there is an export option in R0 linked to an associated import option in the region. For each import incoming into a region, transportation costs are applied and supply limitations are specified (directly or by means of regional infrastructure and transportation processes with possible expansion of infrastructure capacity that requires investment).

The future projected costs of new electricity generation capacities are crucial input into the database. The cost of new generating plants plays an important role in determining the mix of capacity additions and determine how new capacity competes against existing capacity, and against each other in the future. The plants costs are also critical for the model's response to the imposition of environmental controls or any limitations on greenhouse gas emissions.

The current and projected future costs of energy-related capital projects, including new electricity generation plants, have been subject to considerable change and the EIA updates its cost and performance assumptions annually, as part of the development cycle for the AEO (for more details see Refs. [15–19]). Table A1 (see Appendix A) summarizes the updated cost estimates for the generation plants represented in EIA's model that were applied in EPAUS9r.

In a long term dynamic model such as MARKAL, the characteristics of future technologies inevitably change over the sequence of