Energy 75 (2014) 483–500

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Market power, fuel substitution and infrastructure – A large-scale equilibrium model of global energy markets☆

Daniel Huppmann [a,*], Ruud Egging [b]

[a] German Institute for Economic Research (DIW Berlin), Germany
[b] Department of Industrial Economics and Technology Management (IØT), NTNU, Trondheim, Norway

ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form
23 July 2014
Accepted 1 August 2014
Available online 30 August 2014

Keywords:
Energy system model
Infrastructure investment
Strategic behaviour
Mixed complementarity problem (MCP)
Generalized Nash equilibrium (GNE)

ABSTRACT

Assessing and quantifying the impacts of technological, economic, and policy shifts in the global energy system require large-scale numerical models. We propose a dynamic multi-fuel market equilibrium model that combines endogenous fuel substitution within demand sectors and in power generation, detailed infrastructure capacity constraints and investment, as well as strategic behaviour and market power aspects by suppliers in a unified framework. This model is the first of its kind in which market power is exerted across several fuels.

Using a data set based on the IEA (International Energy Agency) World Energy Outlook 2013 (*New Policies* scenario, time horizon 2010–2050, 30 regions, 10 fuels), we illustrate the functionality of the model in two scenarios: a reduction of shale gas availability in the US relative to current projections leads to an even stronger increase of power generation from natural gas in the European Union relative to the base case; this is due to a shift in global fossil fuel trade. In the second scenario, a tightening of the EU ETS emission cap by 80% in 2050 combined with a stronger biofuel mandate spawns a renaissance of nuclear power after 2030 and a strong electrification of the transportation sector. We observe carbon leakage rates from the unilateral mitigation effort of 60–70%.

1. Introduction

The global energy system is constantly changing, driven by technological advances and economic shifts as well as regulatory interventions. The shale gas boom in the United States, for example, drastically shifted the economics between the different fossil fuels. Other trends are a result of governmental regulation, such as the establishment of an ETS (Emission Trading System) by the European Union, or biofuel mandates in North America and Europe. Many of these regulations are motivated by potential threats of global warming and climate change (cf. Ref. [28]), and intend to curb GHG (greenhouse gas) emissions – most importantly CO_2 (carbon dioxide) – or reduce local air pollution. Other measures are motivated by public pressure, for instance the nuclear phase-out in several OECD (Organisation for Economic Co-operation and Development) member countries following the Fukushima incident. Another driver of energy policy interventions are concerns regarding security of supply and import dependency, which have been raised in Europe in particular by the recurring natural gas transit disputes between Russia and Ukraine [35].

When combined, these trends may create paradoxical effects. For example, the shale gas boom in North America led to an increase of coal exports from the US to Europe, and Germany saw an increase in the use of coal and lignite in recent years [2]. This occurred despite the EU ETS, as well as ambitious national policy goals to reduce CO_2 emissions and substantial renewable energy feed-in. At the same time, European policy makers express concerns about a loss of competitiveness with North America due to low energy prices overseas [27] – while European utilities consider mothballing natural gas power plants, because they are not able to

☆ The model presented in this article was developed within the research project "RESOURCES: International Resource Markets under Climate Constraints – Strategic Behavior and Carbon Leakage in Coal, Oil and Natural Gas Markets", funded by the German Ministry of Education and Research (BMBF) within the research framework "Economics of Climate Change". We gratefully acknowledge travel grants by the German Academic Exchange Service (DAAD) and the Research Council of Norway (NFR grant IS-DAAD 225197), as well as funding for R. Egging from the Centre for Sustainable Energy Studies – FME CenSES (NFR grant 209697). We are much obliged to Franziska Holz, Philipp M. Richter, Roman Mendelevitch, Zhonghua Su, Christian von Hirschhausen, and Asgeir Tomasgard for their support and many helpful discussions. The following students provided valuable assistance in data collection and model calibration: Etienne Berthet, Benjamin Boldt, Nicholas Bradford, Quang Huy Nguyen, Michael Rose, Shayna Rose, and Lukas Wuttke.

* Corresponding author. Tel.: +49 30 89789 378.
E-mail address: dhuppmann@diw.de (D. Huppmann).

http://dx.doi.org/10.1016/j.energy.2014.08.004
0360-5442/

compete with subsidized renewables and coal at current low CO_2 permit prices.

There is one further intricate aspect with regard to energy and emissions: carbon leakage. Unilateral or regional emission reduction may shift fossil fuel consumption to other regions and thus have limited benefit to the global climate. This effect can work either directly through reduced world prices for fossil fuels, increasing consumption in other regions; or it may work indirectly via the goods market channel, where production of consumer goods is shifted to regions with lower environmental standards, and the goods are then exported to the high-standards countries. EITE (Energy-intensive and trade-exposed) industries such as steel or pulp-and-paper are particularly vulnerable in this regard, further fuelling the fear of reduced competitiveness and industry relocation.

These examples illustrate the complex and integrated nature of global energy markets and climate policy. This interdependence poses various challenges to companies, governments and supranational entities when considering long-term trends. To gauge the economic impacts of technology-related shifts as well as the effects of regulation and policy measures on the global energy system, policy makers and academics rely on large-scale numerical models of the energy sector.

There is an inherent trade-off in energy modelling: a broad research scope requires substantial aggregation, which necessarily omits many details; on the other hand, many relevant questions with regard to energy, in particular infrastructure investment, can only be tackled adequately while accounting for operational or seasonal detail. Depending on the research question posed, models therefore set different priorities and vary with respect to spatial disaggregation, the time horizon under consideration, and the level of detail with which fuels and technologies (e.g., in power generation) are modelled. They also treat different variables as endogenous (i.e., determined by the model) or exogenous (i.e., taken as a given parameter from some external source or assumption).

Energy market modelling approaches can be broadly classified into four categories, albeit the distinction is not always clear-cut and there is some overlap. IAM (*Integrated assessment models*) such as ETSAP-TIAM [34] and MIT-EPPA [29] typically have a global and long-term scope and explicitly capture the interaction between the economy, the energy sector, and climate. Several CGE (*computable general equilibrium*) models specifically include emissions and climate aspects, for example PHOENIX [42] or GTAP-E [36].

ESM (*Energy system models*) abstract from other sectors of the economy and focus only on the energy sector; this allows for an even more detailed analysis. ESM are usually based on an explicit optimization or equilibrium model.[1] Examples include the PRIMES model [9] and the many applications based on TIMES-MARKAL.[2]

Lastly, *sector models* only cover one particular fuel (e.g., natural gas [15]) or sector (e.g., power generation [32]); this focus allows for the inclusion of a high level of detail with regard to market characteristics, infrastructure constraints (e.g., flow of electricity in a network), or variability over time. Some models in this area of research focus on market structure and strategic behaviour by certain dominant players, which we discuss in more detail below.

[1] Some ESM are “simulation” models, which are not based on any optimization rationale. Rather, there are certain if-then-assumptions or rules underlying the model. To simulate a scenario, the future energy demand or fuel mix is extrapolated based on these rules. Some hybrid models employ a combination of optimization and simulation approaches. For the sake of conciseness, we do not address simulation approaches in detail, but focus on optimization or partial equilibrium-based ESM.

[2] See http://www.iea-etsap.org for more information.

The model we propose in this article combines the advantages of partial-equilibrium modelling (strategic behaviour and a high level of infrastructure detail) with the broad scope of energy system modelling. In particular fuel substitution is included endogenously in the final demand sectors and in power generation. Furthermore, we make provisions for taxes and emission quota on multiple emissions and pollutants at various levels (nodal, regional, global), and we include constraints on the fuel mix in transformation and final demand to represent governmental regulation. This enables us to conduct detailed analyses of the impact of various energy and climate policies on global fossil fuel markets and the integration of renewable energy.

Compared to Ref. [13], this work extends the framework in the following respects: i. it is a multi-period model allowing for endogenous investments in and depreciation of all infrastructure types; ii. it includes seasonality, storage, and load variation; iii. it allows for endogenous fuel substitution in the final demand sectors; iv. the data set is more detailed in terms of geographical coverage, demand sectors, and with respect to the fuels.

The remainder of this paper is organized as follows: the next section details how different model classes tackle fuel substitution, infrastructure, and market power. Section 3 provides the mathematical formulation of the model; Section 4 gives a brief overview of the current data set and presents two scenarios to illustrate the types of analysis that can be performed with the model: a pessimistic scenario regarding the future of shale gas in North America, and a scenario where the EU unilaterally reduces its CO_2 emissions by 80% until 2050. Section 5 concludes and proposes a number of potential avenues for further research and model development.

2. Three modelling aspects of particular interest

Numerical models for assessing potential developments of the global energy landscape have been used for decades. We refer to Refs. [8,23] for a detailed classification and a comparison of models currently used for policy analyses. Instead of providing an extensive overview, we focus on three key aspects, and how they are covered in state-of-the-art models. These aspects are: fuel substitution within demand sectors as well as in power generation; infrastructure for production, transportation, storage, and transformation of different energy carriers; and finally, the explicit consideration of strategic behaviour by certain suppliers, i.e., Nash–Cournot market power exertion. This allows us to highlight how the proposed model departs from and extends the current state-of-the-art in energy modelling.

2.1. Endogenous fuel substitution

There are, in principle, two approaches for incorporating fuel substitution: a *top-down* formulation follows the computable general equilibrium methodology (CGE), using elasticities of substitution. This approach is advantageous because the energy sector can be embedded in the broader economy, thereby allowing for well-founded welfare analyses specifically including the interdependence between economic activity and energy prices. However, due to the large aggregation necessary for such models, many details are lost. In addition, a drawback of using elasticities is that, if a fuel is not used at all in the base year (or only to a small extent relative to total energy consumption), such models are rather inert and are not capable of showing large future penetration rates of these fuels even when economic considerations would warrant that. This is a significant disadvantage when modelling potentially “game-changing” technologies.

In contrast, energy system models (ESM) usually start from a *bottom-up* assessment of the energy sector such as production/