Energy Economics 45 (2014) 373–380

Contents lists available at ScienceDirect

Energy Economics

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

Implementing a load duration curve of electricity demand in a general equilibrium model

Anthony Wiskich ☆

Australian Treasury, Australia

A R T I C L E   I N F O

Article history:
Received 23 December 2013
Received in revised form 23 July 2014
Accepted 29 July 2014
Available online 13 August 2014

JEL classification:
C68
D58
Q4
L94

Keywords:
Computable general equilibrium
Electricity
Load duration curve

A B S T R A C T

Top-down computable general equilibrium models of energy–economy interactions have a limited representation of the electricity sector, typically using constant elasticities of substitution between generation types. Detailed bottom-up electricity models generally have embedded load duration curves with the electricity price determined by the marginal cost of generation. This study incorporates a simple representation of electricity generation with these bottom-up features directly into the GTAP general equilibrium model.

The motivation for this study is to help project generation adjustments and macroeconomic costs associated with policies and shocks affecting the electricity sector. Various scenarios are shown using a simple hypothetical model with Base, Mid and Peak generation types: introducing an incremental output tax on Base generation, assuming mobile capital and then fixed capital; flattening the load duration curve; and introducing an intermittent generation source. Key results are: different responses in electricity generation, price and GDP to a simple constant elasticity of substitution treatment; higher macroeconomic costs associated with a faster tax introduction due to merit order switching and capital decommissioning; an increase in GDP and a shift towards Base generation from flattening the load duration curve; and a displacement of Base generation from the introduction of an intermittent generation source, with variability leading to an increase in Peak generation and a cost to GDP. The model code is made available for replication of results and further application and development.

1. Introduction

Emissions from electricity generation account for a significant proportion of global greenhouse gas emissions and offer abatement opportunities with existing technologies. Therefore, the representation of electricity generation in computable general equilibrium (CGE) or economy-wide models has played an important role in climate change analysis (for example, Clarke et al., 2012). In addition, a CGE model with a detailed representation of electricity generation has other applications, including: demand response analysis, where electricity users adjust demand according to a time-varying electricity price; and analysis of policies or shocks which impact fuel prices.

Representation of electricity generation in a CGE model is typically done via a constant elasticity of substitution (CES) nesting structure between different types of generation. This approach allows substitution between technologies based on price effects and allows different input uses across technologies. For example, GTEM (Pant, 2007) uses a CES (or CRESH) nest between 14 technology types, with elasticity of 5. Phoenix (Sue Wing et al., 2011) nests (with elasticity 1) Base, Intermediate and Peak loads, with different technologies nested (elasticity 4) underneath each. This additional nesting allows differentiation between technologies based on variable versus fixed costs, which are important in electricity markets due to variable aggregate demand and non-storability. The MIT EPPA model (Paltsev et al., 2005) uses a nest (elasticity unspecified) between wind and solar, and other generation types. Other generation typesconsist of the fossil, nuclear, hydro and advanced generation technologies which are treated as perfect substitutes (infinite elasticity). The OECD ENV-Linkages model (Burniaux and Chateau, 2008) uses a CES nest (elasticity 10) between fossil-fuelled, hydro, renewable, nuclear and wind and solar generation types.

For some analysis, an economy-wide model is linked to a detailed bottom-up model. The MARKAL-MACRO model (Manne and Wene 1992) is one example, or the approach taken by Adams and Parmenter (2013). Bottom-up models are typically based on a detailed representation of electricity market operations including generation merit order and marginal pricing. While linking models in this way can be comprehensive, the process is resource-intensive and requires availability of a bottom-up model for each region being modelled. There are also challenges arising from integrating the different models. Using a CES nest structure in the CGE model can be a more practical alternative.

However, while the CES nesting approach allows generation switching between technology types, it is not based on a competitive, marginal-price electricity generation market with variable load demands. I am not aware of incorporation of such a representation

---

E-mail address: Tony.wiskich@treasury.gov.au.

☆ I am grateful for the helpful comments from the editor and referees.

http://dx.doi.org/10.1016/j.eneco.2014.07.021

directly into the GTAP model (Hertel, 1997) or any model using the GTAP database. This paper provides an alternative approach to the CES nest by representing a competitive generation market through identification of variable, fixed and capital costs. The primary objective is to achieve model dynamics in a CGE framework more consistent with a bottom-up approach, without imposing too heavy a burden on implementation. The representation of electricity is necessarily simpler than that contained in detailed bottom-up models, and similar to models with CES nesting, provides an alternative to integrating a CGE and bottom-up model.

In comparison with a CES nesting approach, the potential benefits of the new approach include the following. First, the model exhibits different and varying effective elasticities between technologies, dependent primarily on relative unit variable costs. This may better represent market dynamics and macroeconomic impacts of both small changes in generation and transformational change. Second, the key determinants of results (variable, fixed and capital costs and the load duration curve) typically have various empirical estimates in studies on the electricity market. In contrast, the key determinants in a nested CES treatment are the form of the nest and the elasticities chosen, both of which are often not estimated in electricity market studies. Third, the relative merit order positions of technologies are able to change in the model. In a CES nesting structure using, for example, Base, intermediate and Peak nests, underlying technologies under each are typically fixed. This rigidity may have limitations representing the dynamics of transformational change. Fourth, the approach allows representation of the effects of intermittency (discussed in Section 4), which is difficult to handle in a CES framework.

Section 2 of this paper presents the framework used to integrate the structural electricity market representation into the economy-wide model, called MELD (Model of Electricity with Load Duration). Using a simple hypothetical model, some of the dynamics are demonstrated in Section 3. Section 4 discusses the inclusion of intermittent generation in MELD, and Section 5 concludes.

2. Model description

At the heart of the representation of electricity generation in MELD is a load duration curve (LDC), which shows the frequency of a particular level of electricity demand that occurs in a year (for example, International Energy Agency (IEA), 2012). A stylised version of this duration curve has been implemented in MELD, shown in Fig. 1.

A maximum demand of 2M occurs at point A and minimum of M at point H, roughly based on empirical evidence (for instance, International Energy Agency (IEA), 2012). Different representations of the LDC could be done in MELD: for example, in Section 4 the LDC is adjusted to account for intermittent generation. Electricity generation can consist of any number of different technologies or generators. For this paper just three types of generation are assumed: Base, Mid and Peak. This keeps the model simple while still allowing a demonstration of differing substitution between types in response to a shock.

The capacities of Base, Mid and Peak generation are $\overline{OP}$, $\overline{PQ}$ and $\overline{QR}$ respectively. The ordering is determined by the marginal cost of electricity generation with the lowest marginal-priced generator at the bottom. If total electricity demand in a period increases, the LDC lifts proportionately to maintain the structure as described. Average utilisation rates vary between generation types, with the highest rate for Base of OPFHI/OPGI while Mid and Peak have rates of PQDF/PQEG and QRBD/QRCE. The average utilisation rate for all generation capacity is high at just over 75%, partly as no account is made for maintenance or unplanned outages or for reserves.

To keep the implementation simple, the merit order in MELD is fixed for each period, and any change in the merit order takes effect in the following year. This approximation does not have significant repercussions for the scenarios that have been run for this paper. However, this implementation may need to be revisited as part of conducting further analysis.

At any point in time, the electricity price varies according to aggregate electricity demand. A competitive market operates for each generator type and the electricity price equals the unit variable cost of the marginal generator. Base is the marginal generator type for duration $\overline{JI}$, Mid for $\overline{KJ}$, and Peak for $\overline{LK}$. For the duration $\overline{OL}$ electricity demand exceeds supply and the electricity price is the market price cap (MPC) set by the market regulator. This period allows Peak generation to be paid above unit variable costs to cover capital and fixed costs (another approach would allow Peak generation to bid at a markup over unit variable cost). The initial MPC is set so that demand exceeds supply for just over 3 h per year, which means unserved energy of about 0.0005% of total energy consumption. For comparison, this complies with the reliability target for maximum unserved energy in the National Electricity Market in Australia of 0.002% (Australian Energy Market Commission (AEMC), 2012). For this paper, a closure is used so that demand exceeds supply for a constant period and the MPC is endogenous. The electricity price faced by electricity users is the average price over the whole duration, and the total electricity generated is equal to the area ORBHI.

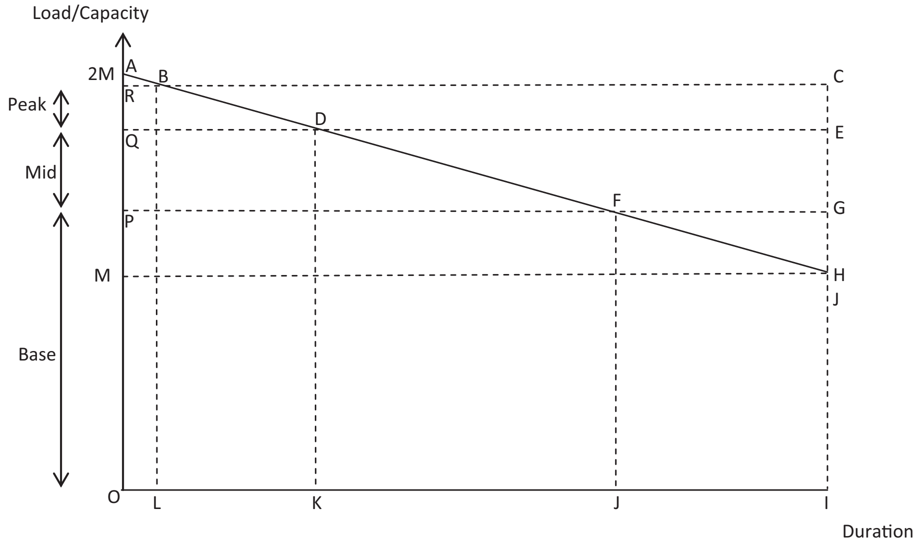

Fig. 1. Load duration curve.