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Mathematical properties and constraints representation for bottom-up approaches to the evaluation of GHG mitigation policies

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ABSTRACT

Bottom-up models, including MARKAL, MESSAGE and AIM, are widely used when analyzing the effect of greenhouse gas (GHG) abatement policies. These bottom-up models are mostly formulated as a linear programming (LP) optimization model to find both the minimal cost combination of abatement technologies and energy flows while satisfying demands. It is not unusual that the bottom-up modeling involves a great number of technical, industrial, socioeconomic and environmental constraints. Investigating representative constraints needed for analyzing GHG abatement policies, this study proposes how to implement these constraints in bottom-up modeling.

1. Introduction

There are two types of modeling approaches for identifying options required to meet greenhouse gas (GHG) abatement targets and assessing their economic impacts: top-down and bottom-up models (Hashim et al., 2005; Wei et al., 2006; Detlef et al., 2009; Loughlin et al., 2010). Top-down models investigate a broad equilibrium framework, which addresses the macroeconomic impacts of climate policies on the national and global scale, by evaluating the system based on aggregate economic variables such as output, consumer prices and GDP. As such, details on specific technological options may not be properly captured. Featuring a large number of specific technological options, on the other hand, bottom-up models focus on analyzing project-specific climate change mitigation policies such as fuel economy and mode changes (Fishbone and Abilock, 1981; Messner, 1997). These models are typically cast as optimization problems to obtain the least-cost combination of energy system activities to meet a given demand for useful energy subject to technical restrictions and energy policy constraints (Böhringer and Rutherford, 2005). Interested readers may refer to IPCC (1995, 2001) for an extensive discussion on the differences between top-down and bottom-up models. Examples of the bottom-up optimization models include MARKAL (Market Allocation), MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts), and AIM (Asian Integrated Model), all of which are developed based on linear programming (LP) with a few differences in user interface and database utilization. Based on an extensive literature survey on the bottom-up models for the transportation sector, it has been found that there are several useful constraints which have not been properly addressed.

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This article deals with how to represent these constraints in a mathematical form and incorporate them in bottom-up modeling.

In bottom-up modeling, the energy service demands of different sectors are usually exogenously given. Alternative abatement technologies and energy flows represented by the so-called 'reference energy system (RES)' are then investigated in order to satisfy service demands. Thus, the most important aspects of bottom-up modeling are how to derive service demands and RES (Fishbone and Abilock, 1981; Messner, 1997). Energy service demands indicate the amount of final products of a sector that should be met for each analysis period, and the definition of service demands is dependent upon the corresponding sector. For example, service demands of the passenger vehicle sector may be defined by the number of vehicles or travelled distance. Likewise, the production of power measured in megawatt-hours (MWh) may be service demands for the power generation sector. The identification of service demands for individual sectors is followed by the development of RES. As a network representation of energy flows in the corresponding sector, the RES is composed of various elements such as energy forms, technologies, resources, storages, etc. Fig. 1 depicts an example of RES for the transportation sector.

Represented by the vertical lines in the RES, an energy form corresponds to an energy or material used for the production of final products. For instance, there are five energy forms in Fig. 1 such as oil, bio ethanol, electricity, gasoline–bio ethanol, and vehicle travelled distance in km/year. A set of energy forms close to each other constructs an energy level, and thus there are three energy levels such as car energy, blended energy, and car demand. The energy level 'car energy' consists of three energy forms, i.e., oil, bio ethanol, and electricity. The last energy level in an RES is correspondent with energy service demands, and thus the service demands in Fig. 1 are the energy level 'car demand'. Energy flows in relation to service demands may be effectively represented in an RES. Each rectangular box represents a technology, which may be classified into three categories: energy, process, and demand technologies. Energy technologies are those to produces energy (e.g., mining, import, etc.). They do not have any inputs, but only have outputs of energy. Oil imports via oil carriers are an example of energy technology. Process technologies transform an energy form to another form. Blending oil and bio ethanol is an example of process technology, which produces a blended energy (BE). Demand technologies create service demands with an input of energy. The demand technology 'electric car' produces 100 km of vehicle travelled distance by consuming 12 kWh of electricity. Combining a certain amount of individual demand technologies, the service demands of 20 billion km/year should be satisfied. There are a great number of possible combinations of demand technologies satisfying the service demand. The proportion of each demand technology may be highly variant. For example, all the service demands may be covered by a single demand technology alone, or each demand technology may split up the service demands evenly. Further, depending on the proportion of individual demand technologies, the amount of energy forms used may also be enormously diverse.

Based on the RES, two types of main constraints in a bottom-up LP model are constructed to ensure the balance of energy flows while satisfying the given amount of service demands. First, an energy flow balance constraint states that the supply and demand for each energy form should be equivalent. Second, service demands generated by demand technologies should be greater than or equal to the given amount of yearly service demands. For each of the existing and new technologies, a variety of attributes, such as cost, activity, capacity, etc., are required to construct these constraints. For example, attributes associated with demand technology 'passenger vehicles' include the prospective price of their energy resources (e.g., gasoline, diesel, and LPG) along with their fuel efficiency, vehicle price, and vehicle mileage per year. Decision variables in an LP model of bottom-up approach are capacity and activity variables. The capacity variable is related to the installation of new technologies whereas the activity variable indicates the amount of energy to operate the installed technology. In addition to the main constraints mentioned above, one may need to consider additional constraints for individual technologies, such as

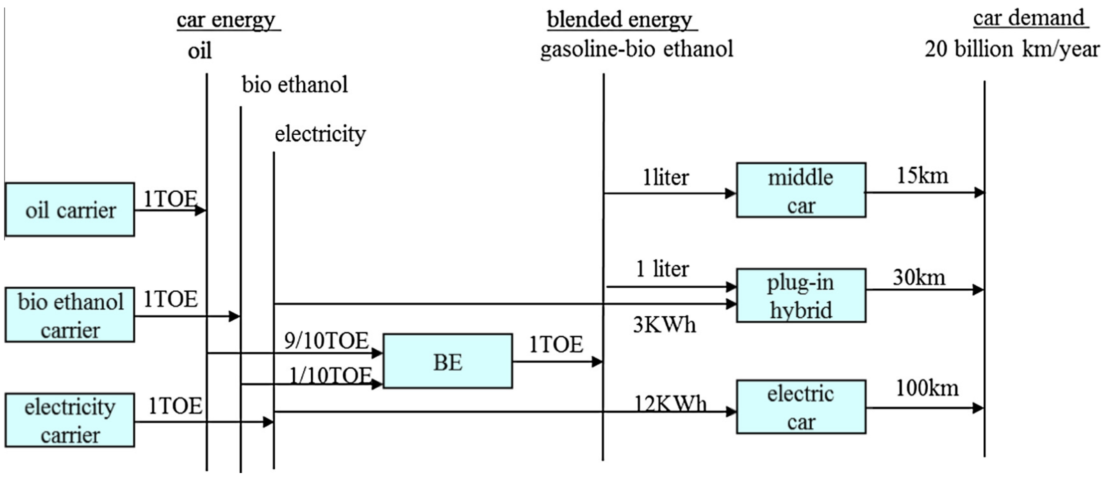

Fig. 1. Example of RES for the transportation sector.