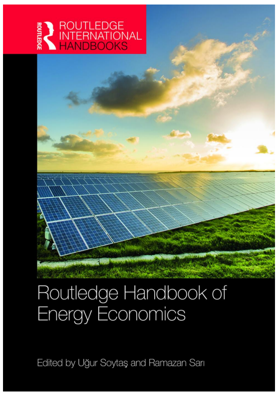

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Top-down and bottom-up models

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Top-down and bottom-up models

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Energy is a crucial intermediate input in production activities as well as a final consumption good that has progressively gained considerable importance in recent times more than ever before. Energy has come into prominence not only because the demand for energy has remarkably increased and it has been an integral part of economic activities, but also due to the scarcity of natural energy resources as well as the environmental problems that accompany increased energy use. As a result, the need has emerged for economic models that embody energy as an explicit input and are also capable of addressing environmental concerns. Although the literature on energy modeling has a long history, it began proliferating in the 1970s with the sharp increases in energy prices due to the first oil crisis in 1973. The impacts of energy prices on economies revealed the need for modeling approaches in which the link between economic activities and energy use is represented. Thereafter, great progress occurred in the efforts to create such links, from basic relationships to sophisticated procedures and theoretically consistent frameworks over the course of time. This chapter scrutinizes these linking efforts on the basis of two broad modeling paradigms: top-down (TD) and bottom-up (BU) modeling. First, brief descriptions of these modeling paradigms are given with their general characteristics, advantages, and drawbacks. Attempts at linking the two models are then presented. Finally, the chapter ends with concluding remarks.

1 Two modeling paradigms: bottom-up (BU) and top-down (TD)

There are various ways to classify the models representing the interaction between energy and the economy since these models are very diverse in their characteristics. These classifications may be based on the spatial coverage, assumptions, planning horizon, degree of endogenization, underlying methodology, sectoral coverage, mathematical approach, and so on. However, over the course of time, researchers have come to agree that there are two broad and widespread modeling approaches, TD and BU (Grubb et al., 1993), categorized according to the perspective from which the models are created. The two modeling approaches differ mainly with respect to the emphasis attributed to technological details of the energy system and to the consistency of the models in terms of economic theory. Conventional BU models treat energy systems starting from primary energy extraction activities including conversion, refining, transport, and distribution processes to the end-use of the energy commodity without paying much attention to interactions with the rest of the economy. Conventional TD models, on the other hand, provide an extensive representation of the overall economy along with interactions between sectors. Moreover, these models reflect the microeconomic decision-making rationale of the agents in the economy or macroeconomic feedback relating the energy sector to other sectors in the economy, but they have a limited representation of the current practices and lack in the application of new technologies. The rest of this section is devoted to a detailed description of these two approaches.

1.1 BU models

Conventional BU models mainly seek a plan that matches the intertemporal energy supply with the demand, where the energy sector is represented in technological detail, especially on the supply side. These models portray the energy sector from an engineer's point of view, which is why they are also called engineering models. Optimization tools, especially linear and nonlinear programming, are widely used in order to find solutions in BU models where the objective is considered to be the minimum cost or the maximum profit plan. However, there is a wide range of studies employing other objectives (e.g. maximizing social welfare) or multiple objectives (e.g. joint optimization of cost and emissions) (Antunes & Henriques, 2016), as well as studies in which side constraints (e.g. supply security, reliability or emission constraints, import restrictions), considering the concerns of the decision-makers, are embedded.

Although there exist BU models that include a high level of detail in technological options, exhaustive regional disaggregation, or high temporal resolution, here it is preferred to follow the notation of (Böhringer & Rutherford, 2009) to describe the conceptual BU model for the sake of simplicity and to help the reader better grasp the linking concepts that will be presented in the following sections.

$$max\ p^T \left[e - x\right] \tag{32.1}$$

subject to

$$Ax + Bz \leq Ce \tag{32.2}$$

$$e, x \geq 0 \tag{32.3}$$

$$l \leq z \leq u \tag{32.4}$$

Here, p^T is the price vector, while e and x are energy sector supplies and demands, respectively. $A, C \in R^{Mxn}$ and $B \in R^{MxN}$ denote technical constraints and $z \in R^N$ stands for energy system variables, while l and u are lower and upper limits on z, respectively. The objective (Equation (32.1)) is to maximize the total profit in the energy sector subject to technical constraints (Equation 32.2)) as well as non-negativity inequalities for e and x (Equation 32.3)) and lower and upper bounds on z (Equation 32.4)).

BU models are also classified as partial equilibrium models since they focus on a specific sector (i.e. they do not employ an endogenous mechanism to represent the macroeconomic feedbacks from the rest of the economy). The energy demand in BU models is usually exogenous or represented via a simple relationship depending on several exogenous factors, such as GDP growth, population growth, primary energy prices, and so forth, that trigger the change in sectoral or overall energy demand. These models, on the other hand, give the description of current and prospective supply technologies in detail where these technologies compete with each other based on their financial and technical characteristics such as initial investment, fixed and variable overhead and maintenance costs, the duration for which they can operate, fuel costs, decommissioning costs, technical efficiency, and so forth. Moreover, BU models might consider not only the supply of final energy but also the extraction and conversion activities as well as reserve availabilities. Environmental characteristics (emission or pollution coefficients) of the technological options are also taken into account for BU models with an environmental component.

As noted for energy models in general, there are also numerous BU models differing from each other by their spatial coverage, planning horizon, sectoral coverage, and so forth. However, there are two modeling families, MARKAL (an acronym for MARKet ALlocation; Loulou et al., 2004a) and MESSAGE (Schrattenholzer, 1981), which have come to the forefront with their extensive ability to represent energy systems comprehensively. Moreover, their flexibility enables them to be used for a wide range of purposes in different regions. These models draw their strength mainly from ongoing improvement efforts that have been continuing for years. The term "family" is used for these models since not only have various extensions of them been developed, in which stochastic or dynamic features are incorporated, but also these models are integrated into several other models that focus on other sectors as well as the overall economy or address policy issues such as greenhouse gas (GHG) mitigation or land use.

1.2 TD models

Conventional TD models deal with the whole economy in an aggregated fashion. The energy sector in these models is either just one of those sectors in the overall economy without a specific treatment or it is a differentiated sector with limited specification. Contrary to BU models, these models put more emphasis on economy-wide market interactions and represent the flow of factors of production, commodities, and income across the whole economy in a certain region or at a national or global scale. Although Ramsey growth models (e.g. DICE and RICE; Nordhaus & Boyer, 2000), macroeconometric models (e.g. Danmarks Statistik, 1996; Chapter 33 in this handbook), or input-output models (e.g. Fathurrahman et al., 2015; Chapter 8 in this handbook) are also employed as TD energy models, this section focuses on computable general equilibrium (CGE) models in line with the predominant trend in the literature. The reader is referred to Chapter 30 in this handbook for a general comparative discussion of CGE models.

CGE models represent the interaction of agents in a Walrasian economic equilibrium system, which was formalized by Arrow and Debreu (1954), and provide a portrayal of the circular flow in an economy. Households own the factors of production and consume the end goods, and firms produce goods and services by using the factors of production that they rent from the households. The government is usually described as a passive agent that collects taxes from activities or institutions and distributes them through transfer payments. CGE models have become the main tool in addressing the real-world consequences of policies on employment, taxation, public finance, international trade, and climate change as well as energy-related issues, where impacts of different policy alternatives on welfare, income, sectoral/overall output, and relative prices can be assessed. It was not only the developments in computing technology but also the availability of software packages as well as data that fit the modeling requirements that led this approach to become prevalent among policy analysts.

CGE models use simplified and stylized functional forms to define smooth continuous production and utility functions where the parameters are estimated based on historically derived relationships. The profit-maximizing behavior of producers and utility-maximizing behavior of consumers based on neoclassical economic theory are then completely defined within the framework of these functional forms. Given that a CGE model is a system of nonlinear equations where the number of equations is equal to the number of variables, the model can be formulated as a nonlinear optimization problem with a dummy objective or as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995). The activities of different agents in the economy are described by three types of conditions in a CGE model (Paltsev, 2004):

- *Zero-profit conditions*: These conditions require that the value of inputs be equal to or greater than the value of outputs (i.e. any activity operated at a positive level must earn zero profit). Such a condition can be described as follows:

  $$-\mathit{profit} \geq 0; \mathit{output} \geq 0; \mathit{output}^T \left(-\mathit{profit}\right) = 0$$

- *Market-clearing conditions*: These conditions imply that supply must be equal to demand for each commodity with a positive price. Such a condition can be described with the following expression:

  $$\mathit{supply} - \mathit{demand} \geq 0; p \geq 0; p^T \left(\mathit{supply} - \mathit{demand}\right) = 0$$

- *Income-balance conditions*: For each agent, including the government, expenditures must exhaust the total income (value of factor endowments and tax revenue):

  $$\mathit{income} = \mathit{endowment} + \mathit{tax\ revenue}$$

CGE models are calibrated, that is, parameters for utility and production functions are estimated, based on a social accounting matrix (SAM), which is a matrix representation of national accounting balances. A schematic representation of a SAM can be seen in Figure 1.1 (Sue Wing, 2004)

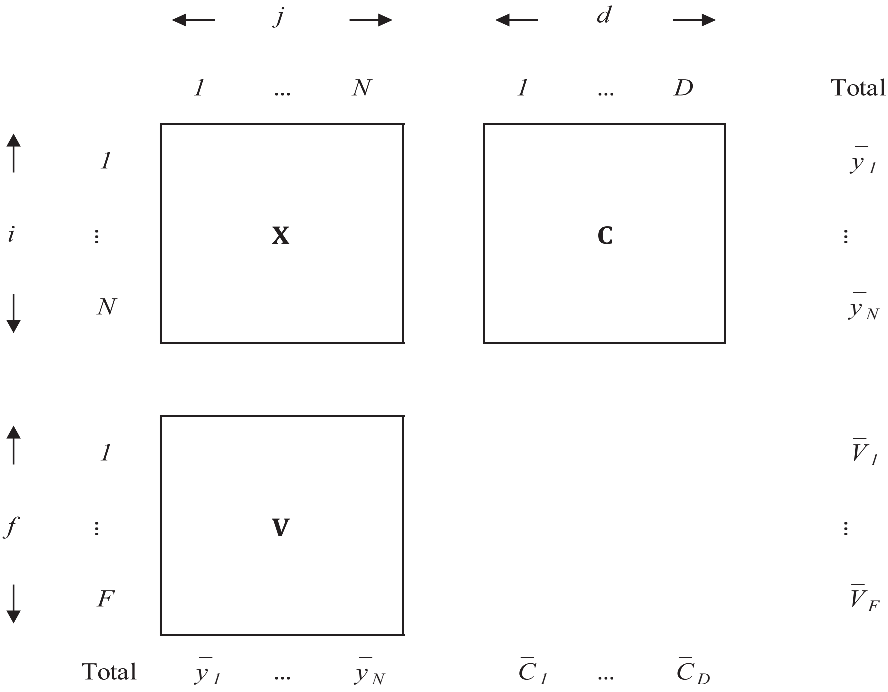

Figure 32.1 Schematic representation of SAM

where X, C, and V represent the intersectoral flows, final demand, and value-added activities, respectively. Each account is represented by a row and a column, and the cell entries denote a payment from the account of a column to the account of a row. Note that the balance of row and column sums together with the balance of the sum of entries in C and V ensure that the aforementioned equilibrium conditions (zero-profit, market-clearance, and income-balance) are satisfied.

In TD models, energy is generally treated as an explicit factor of production together with conventional ones. Representing the energy sector and specifically the power sector through aggregate production functions simplifies the activities in these sectors when the discrete nature of the technologies in these sectors is taken into account. Thus, this representation is too elementary to capture technology choices in the energy sector. As noted earlier in this section, CGE models have become the main tool in analyzing the real-world consequences of a wide range of policies not limited to energy or climate change issues. There are several CGE models that are specifically well suited to address energy-related policies, such as the MIT Emissions Predictions and Policy Analysis (EPPA) model (Babiker et al., 2001; Chen et al., 2015; Paltsev et al., 2005); GEM-E3 (Capros et al., 2013), used by the European Commission; the Phoenix Model (Sue Wing et al., 2011), developed by the Joint Global Change Research Institute at the University of Maryland; GEMINI-E3, developed jointly by the French Ministry of Equipment and the French Atomic Energy Agency with the collaboration of the Swiss Federal Institute of Technology (Bernard & Vielle, 2008); and the OECD's ENV-Linkages model (the successor of GREEN) (Château et al., 2014).

2 Integration of top-down and bottom-up models

TD and BU approaches originated from different fields with different purposes. The energy sector in conventional TD models is usually represented in an aggregate manner via smooth production functions as noted in the previous section; thus, these models lack in representing the current discrete energy technologies and costs, and in their time-varying behavior, as well. Moreover, the conservation of matter and energy may be violated in TD models. Conventional BU models, on the other hand, describe current and backstop technologies in detail while they lack in the ability to capture price distortions, economy-wide interactions, and income effects (Böhringer & Rutherford, 2006). These key differences between the two modeling approaches lead to inconsistent outcomes (Grubb et al., 1993; Wilson & Swisher, 1993). More clearly, TD models show a higher use of energy due to the assumption of significant unexploited opportunities in BU models for cost-effective investments in energy efficiency (Koopmans & te Velde, 2001).

The two approaches substantially complement each other rather than opposing each other. Thus, given the shortcomings of both paradigms, there have been considerable attempts of proposing a model that combines the BU and TD approaches since a complete analysis of policies related to energy production and consumption needs to incorporate the strengths of each paradigm. As indicated in Section 1.2, the two modeling approaches differ mainly with respect to the emphasis attributed to technological details of the energy system and consistency in terms of economic theory. Accordingly, as discussed by Hourcade et al. (2006), there are three main dimensions that characterize an energy-economy model: technological explicitness, macroeconomic completeness, and microeconomic realism. Conventional BU models lie on the technological explicitness-macroeconomic completeness layer, whereas conventional TD models lie on the macroeconomic completeness-microeconomic realism layer while researchers in this field pursue an ideal model with a representation of all dimensions to some reasonable extent.

The efforts to integrate BU and TD models (i.e. to create hybrid models) achieve a certain level of success in each of the three dimensions in various ways. Before an in-depth analysis of these efforts, it would be helpful to touch on two crucial paradigms in coupling BU and TD models: the "soft link" and the "hard link". The definitions of "soft link" and "hard link" (also called "informal" and "formal" linking; Wene, 1996) in the literature differ with slight nuances; in other words, there is not a consensus among researchers on the definition of or the distinction between soft and hard links (Helgesen, 2013). For example, Wene (1996) explained the difference between the two linking approaches based on whether the information transfer between the models is directly controlled by the user via judgments or by computer programs via formalized procedures. Bauer et al. (2008), on the other hand, used these paradigms only for the integration of a BU model (an energy system model) and a macroeconomic growth model while putting the integrated models of the CGE modeling framework in another class.

Jacobsen (1998) defined "hard-linking" as integrating the models with interactions in an iterative procedure. However, a more common classification applied in various other studies (Böhringer & Rutherford, 2008, 2009; Lanz & Rausch, 2011a) is to define "soft-linking" as integrating the existing separate large-scale BU and TD models in an iterative manner until convergence in key parameters is satisfied while referring to "hard-linking" as the complete integration of the models. In these studies, besides the soft-linked and hard-linked models, a third approach is identified in which a reduced form of one model, either TD or BU, is integrated or embedded into the other. The classification scheme in this chapter is closest to this approach, with a slight difference: the last category (integration of a core and a reduced form model) is also accepted as a "hard link" in line with the work of Riekkola et al. (2013). Hybrid modeling efforts are discussed in the remainder of this section based on this classification scheme. First, the models with a "soft link" are explained. Subsequently, models with a "hard link" are presented within two subsections: integration of a core model with a reduced form model, and completely integrated models.

2.1 Soft-linked models

In soft-linked models, existing models are coupled in such a way that the information between the models is transferred until a predetermined convergence criterion is satisfied. However, there exist several complications in this approach since the two modeling paradigms of BU and TD are introduced to serve for different purposes and analyses to answer different research and policy questions (Jacobsen, 1998). Moreover, the models significantly differ in their behavioral assumptions and accounting systems (Böhringer & Rutherford, 2008). Thus, achieving overall consistency between these models is not straightforward.

Attempts to develop soft-linked models date back to the end of the 1970s. Hoffman and Jorgenson (1977) combined an econometric model of interindustry transactions for the US economy with a process analysis model of the energy sector (the Brookhaven Energy System Optimization Model (BESOM)), where the former transfers demand for energy outputs while the latter provides resources, technologies, prices (some of them dual prices obtained from BESOM), and capital requirements as well as environmental information. Another attempt at a soft-linked model is HYBRIS (Jacobsen, 1998), in which three BU modules (energy supply, electricity demand in households, and heat demand in households) and a national TD model of Denmark are linked where the TD model is used as it is while the BU modules are reorganized for integration. This study also provided an insight into linking problems such as different responses to impacts of energy price changes or income developments. Messner and Schrattenholzer (2000), on the other hand, integrated a TD model, MESSAGE, with a BU model, MACRO, via a fully automated link, emphasizing that the integrated model demonstrates more transparency compared to hard-linked models including similar TD and BU components. The integrated model iterates for each period until the supply curves (transferred from MESSAGE to MACRO) and demand curves (transferred from MACRO to MESSAGE) are matched in 11 world regions, where the iteration process is triggered by exogenous growth rates of GDP and energy intensity reduction that comes from a separate scenario generator module. Martinsen (2011) proposed the integration of the national macroeconomic model MSG6 and the MARKAL Norway model with the introduction of technology learning from a third model, a global technology-rich energy systems model, ETP. The calibration and consistency check phases are carried out over electricity generation and associated cost figures.

Drouet et al. (2005) developed a soft-linked model for Switzerland by using reduced forms of the dynamic-recursive CGE model GEMINI-E3 and the BU model ETEM-SWI, which they called GEMINI-E3S and ETEM-RES. The integration focuses on the residential sector; thus, the sector is removed from the TD model and the BU model is designed only for the residential sector. The model iterates until the convergence criterion on the level of carbon prices is satisfied while the carbon taxes, energy prices, and useful energy demands are transferred from the TD to the BU model and final energy demands and carbon emissions flow in the opposite direction. The GEMINI-E3 model was coupled with TIAM-WORLD in another study by Labriet et al. (2015), which differs from the other soft-linked models as TIAM-WORLD itself is an integrated model with price-elastic final energy service demands. The coupling requires a detailed mapping between the two models in terms of the regions, the activity sectors, and the energy goods. Another sectoral integration attempt is that of Schäfer and Jacoby (2006), which couples the MIT EPPA model with the MARKAL model of transport technology. However, since the transportation sector in EPPA is aggregated, a third model, a model of modal splits, is employed to satisfy consistency with the disaggregated BU representation. The iterative process between the models takes place over the energy use in the models. Labandeira et al. (2009) analyzed the impacts of the European Union Emissions Trading Scheme (ETS) on the Spanish economy by using an integrated model in a similar setting where the BU model is formulated as an MCP. The work of Fortes et al. (2014) differs from these studies with its coverage in linking, which they call "full-link", not focusing on integration over a single sector but rather over all sectors. The proposed model, HYBTEP, integrates the national TD model GEM-E3_PT with the national BU model TIMES_PT for Portugal. There are also two linking modules, a demand generator and an energy link, between the models. The models are run independently for the whole planning horizon and iterations are carried out by checking whether the maximum deviation between the two models over all sectors is below the predetermined threshold level.

2.2 Hard-linked models

Integration of a core model with a reduced form model

Unlike the iterative process employed in soft-linked models, hard-linked models are integrated in a single framework in which the solution is obtained via simultaneous optimization. Almost all the models presented in this section couple a core BU model with a reduced form of the TD model, where the non-energy sectors are represented in an aggregated fashion (i.e. a one-sector economy without sectoral disaggregation). The models, in other words, link the physical process analysis with a long-term macroeconomic growth model. The pioneering study in this genre of modeling is ETA-MACRO (Manne, 1977), which is the predecessor of GLOBAL 2100 (Manne & Richels, 1990), MARKAL-MACRO (Manne & Wene, 1992), and the MERGE model (Manne et al., 1995). Moreover, there are further extensions of MARKAL-MACRO models (Bahn et al., 1999; Kypreos, 1996; Loulou et al., 2004b; Strachan & Kannan, 2008). In the rest of this section, this modeling framework is summarized, employing the notations used in these studies.

The models in this class propose economy-wide solutions by maximizing the sum of discounted utility of consumption (*UTIL*) on the part of a representative household over all periods with a utility discount factor of *udf* (Equation (32.5)), while the aggregate economic output (Y_t) in the economy is calculated using a constant elasticity of substitution (CES) production function (Equation (32.6)), where subscript *t* refers to the year or period. The key feature in this modeling avenue is the links between the energy sector and the rest of the economy via the economy-wide production function as well as the relationship between energy costs (EC_t) and other macroeconomic variables (Equation 32.7)), as shown below:

$$UTIL = \sum_{t=1}^{T} \frac{U\left(C_t\right)}{\left(1 + udf\right)^t} \tag{32.5}$$

$$Y_t = \left[a\left(K_t^{\alpha} L_t^{1-\alpha}\right)^{\rho} + \sum_{dm} b_{dm} D_{dm,t}^{\rho} \right]^{\frac{1}{\rho}} \tag{32.6}$$

$$Y_t = C_t + I_t + EC_t \tag{32.7}$$

Here, $\rho = \left(\dfrac{\sigma - 1}{\sigma}\right)$, σ denoting elasticity of substitution; *a*, *b* denote scaling factors and $\propto$ denotes the value share of capital. K_t and L_t represent capital and labor, and $D_{dm,t}$ is the demand for energy services of type *dm* in year *t*. C_t and I_t represent consumption and investments. (C_t) represents the utility of consumption, which is generally assumed to be the logarithm of the consumption. Note that there are various extensions of the standard version in which the disaggregation of the second aggregate in the production function as well as the nesting structure between capital, labor, and energy inputs or sectoral disaggregation differ (e.g. Kat, 2011; Kumbaroğlu, 1997). Güven (1994) also reformulated the ETA-MACRO model for Turkey to include foreign trade and currency restrictions, where the inclusion of foreign trade enhances the representativeness of the model for countries in which growth is highly dependent on foreign capital inflows.

WITCH, developed by Bosetti et al. (2006), represents another type in this modeling genre, where the core model is a TD model and the BU model is the reduced party. It is a multiregion Ramsey-type neoclassical optimal growth model with a relatively detailed representation for the energy sector (and especially for the power sector). WITCH is a forward-looking model that incorporates a description of endogenous and induced technical change in a game theoretical structure. The works of Edenhofer et al. (2005) and Bauer et al. (2008) are two studies in a similar setting; the former introduces a hard-linked model, MIND, while the latter presents a comparison of soft-and hard-linking approaches with the inference that the simultaneous equilibrium of the energy and capital market is not ensured via the soft-link approach.

Completely integrated models

The other type of hard-linked models originated from several pedagogic studies (Böhringer, 1998; Böhringer & Löschel, 2006; Böhringer & Rutherford, 2005, 2008). The idea in this approach is to cast both models, the TD economic equilibrium model and the BU activity analysis, as MCPs and solve them in a single consistent framework. In other words, a set of discrete BU technologies, mostly related to the power sector, are directly embedded into a top-down CGE model.

As noted in Section 1.2, a competitive market equilibrium problem can be formulated as an MCP (Mathiesen, 1985; Rutherford, 1995). The BU formulation presented in Section 1.1 can also be reformulated as an MCP using Kuhn-Tucker conditions of the problem (Böhringer & Rutherford, 2009) as follows:

$$C^T\pi \geq p;\ e \geq 0;\ e^T(C^T\pi - p) = 0 \tag{32.8}$$

$$p \geq A^T\pi;\ x \geq 0;\ x^T(p - A^T\pi) = 0 \tag{32.9}$$

$$Ax + Bz \geq Ce;\ \pi \geq 0;\ \pi^T\left(Ax + Bz - Ce\right) = 0 \tag{32.10}$$

$$l \leq z \leq u;\ \lambda, \mu \geq 0;\ \lambda^T\left(z - l\right) = 0;\ \mu^T\left(u - z\right) = 0 \tag{32.11}$$

$$\lambda + B^T\pi = \mu \tag{32.12}$$

Note that π is the dual variable of Equation (32.2), whereas λ and μ are dual variables of lower and upper bounds on z. Thus, in fact, Equations (32.8)–(32.12) define all complementarity relations between the primal BU equations and their dual variables and vice versa for the dual BU problem. These equations and the equilibrium conditions put forward in Section 1.2 along with the following equation define the integrated hybrid model.

$$p^T\left[e - x\right] = \mu^T u - \lambda^T l \tag{32.13}$$

Equation (32.13) is a result of the equivalence relation between primal and dual objective values in the optimal solution.

This modeling framework was employed in several studies. For example, Frei et al. (2003) extended the model as a dynamic hybrid model by incorporating the endogenous formulation of investment decisions. Kumbaroğlu and Madlener (2003) developed a backward-looking dynamic CGE model, SCREEN, and demonstrated it for the case of Switzerland. Sue Wing (2006) and Proença and St. Aubyn (2013) developed similar hybrid models for assessing the cost of limiting CO_2 emissions in the United States and the effects of feed-in tariffs to promote renewable energy in Portugal, respectively. The work of Böhringer et al. (2003) differs from these studies in that the agents have forward-looking behavior, unlike the backward-looking, static, or dynamic-recursive models.

An important challenge in merging TD and BU models in a single consistent framework is the compatibility of the data. In other words, the data resources as well as the way they are used in the corresponding models differ significantly from each other. For instance, to achieve a consistent integration between the models, factors of production in TD models should be compatible with not only inputs of BU models but also with the fixed and variable costs of operations or maintenance. Therefore, data reconciliation and use of BU information in a TD model are challenging but essential research avenues in hybrid modeling (Kiuila & Rutherford, 2013; Koopmans & te Velde, 2001; McFarland & Herzog, 2006; McFarland et al., 2004; Peters, 2016; Rodrigues & Linares, 2014, 2015; Sue Wing, 2008).

Instead of employing the ad hoc methods used to disaggregate the energy sector and specifically the power sector in the CGE modeling framework, Sue Wing (2008) proposed a robust and transparent mathematical scheme to reconcile and integrate BU engineering information with TD macroeconomic data. This procedure was then used by Eskeland et al. (2012), whereby a CGE model, GRACE, was extended to include power sector disaggregation and called GRACE-EL. Rodrigues and Linares used a similar routine for extending the power sector disaggregation, but with high temporal resolution (2014, 2015). Peters (2016), on the other hand, developed the GTAP-Power Data Base, an electricity-detailed extension of the GTAP 9 Data Base, by using matrix balancing methods where the GTAP-Power Data Base not only includes technological detail in power generation technologies but also has base/peak load disaggregation.

Although the integrated MCP formulation, with its overall consistency, aroused interest among researchers and was implemented in numerous studies as summarized above, it was realized in practice that the approach has severe limitations due to the complexity and dimensionality that the BU model brings with it (i.e. upper and lower bounds on decision variables with concomitant income effects). A block decomposition algorithm and an iterative solution procedure were then proposed to make this consistent framework practically applicable (Böhringer & Rutherford, 2006, 2009). The decomposition of the integrated model, in fact, implies that these models are not hard-linked anymore, but are soft-linked. Nevertheless, it is preferred to keep them under this heading due to the submodels' close link with the corresponding integrated framework as well as to stick to the theoretical consistency in the decomposition algorithm. Moreover, this approach is also referred to as "hard-linked" in several studies (e.g. Villasana, 2015; Tapia-Ahumada et al., 2015).

A schematic representation of the decomposition algorithm and the iterative solution procedure can be seen in Figure 32.1, in which a TD economic model and a BU electricity model are coupled. It is crucial to have the submodels initially set to a consistent benchmark, which is referred to as data reconciliation and model calibration. After ensuring that the two submodels are consistent, or in other words that the BU power sector input-output figures are consistent with the corresponding figures for aggregated power sector in the SAM, the models are solved iteratively based on the exogenous variables transferred from the other submodel. In each iteration, a convergence check is carried out after the solution of the BU electricity model and the

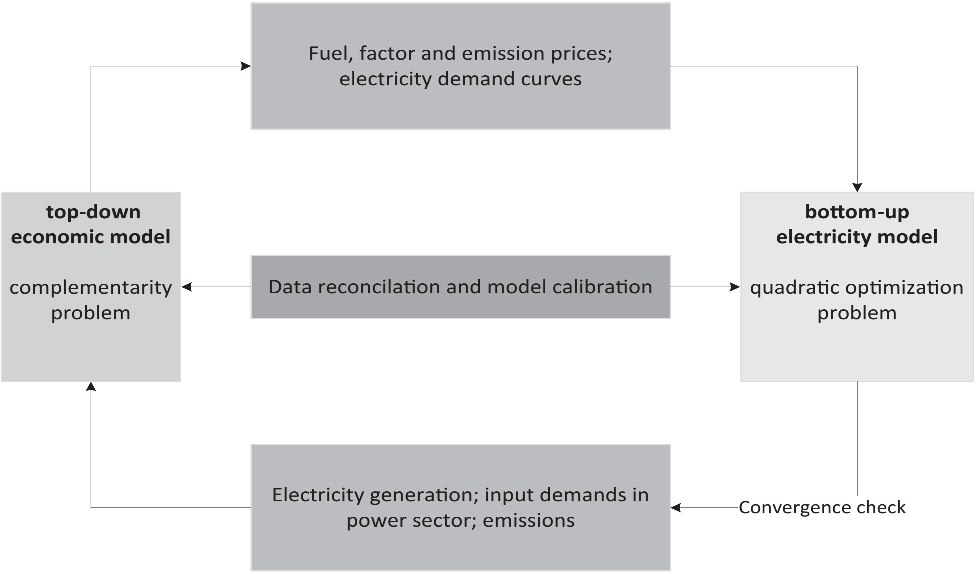

Figure 32.2 Iterative decomposition algorithm based on several previous studies (Böhringer & Rutherford, 2006, 2008; Lanz & Rausch, 2011b; Rausch & Mowers, 2012; Ross, 2014b)

procedure terminates when the maximum deviation in decision variables is under a predetermined threshold between two successive iterations.

One of the key points in the block decomposition algorithm is the need for revision in the objective function of the BU model (i.e. cost minimization/profit maximization) to incorporate the demand response. This is achieved by redefining the objective function as the maximization of total surplus, namely the sum of consumer and producer surplus, which creates a quadratic programming problem (Böhringer & Rutherford, 2009). Moreover, as proposed by Böhringer and Rutherford (2009), "a Marshallian demand approximation in the energy sector provides a precise local representation of general equilibrium demand" and rapid convergence is observed as the energy sector (or specifically the electricity sector) is small relative to the rest of the economy (remember the elephant and rabbit stew metaphor of Hogan & Manne, 1977). However, there are also studies (Villasana, 2015; Tapia-Ahumada et al., 2015) in which the demand response is reflected via an additional iteration procedure only within the BU model while keeping cost minimization as the objective.

The block decomposition algorithm has been implemented in various studies to integrate existing models of BU electricity models and TD CGE models (Hwang & Lee, 2015; Labandeira et al., 2009; Lanz & Rausch, 2011a, 2011b; Villasana, 2015; Rausch & Mowers, 2014; Ross, 2014b; Tapia-Ahumada et al., 2014, 2015; Tuladhar et al., 2009). Tuladhar et al. (2009) proposed the integrated model MRN-NEEM, which couples the TD model MRN (Multi-Region National Model) and the BU model NEEM (North American Electricity and Environment Model). Ross demonstrated the integration of two versions of the Dynamic Integrated Economy/Energy/Emissions Model (DIEM), the DIEM-CGE and DIEM-Electricity models (2014a), in which the block decomposition algorithm is employed (2014b). Hwang and Lee (2015) employed a block decomposition algorithm to analyze policies related to Korean electricity industry reform. The study by Labandeira et al. (2009), which was classified among the soft-linked models, can also be referred to in this section since the BU model is formulated as an MCP in which a price-responsive demand function is incorporated. Lanz and Rausch (2011a) coupled the MIT U.S. Regional Energy Policy (USREP) model with a BU formulation of the electric sector. Rausch and Mowers (2012), on the other hand, coupled USREP with the ReEDS (Renewable Energy Deployment System) model (Short et al., 2011), a recursive-dynamic power generation and transmission expansion planning model focusing on renewable technologies. Tapia-Ahumada et al. (2014, 2015) again used the MIT USREP model as the TD component and developed an integrated benchmark model by linking the USREP to the BU electricity model EleMod to examine the performance of the TD-only approach in terms of modeling intermittent renewable energy. The TD-only approach in that study is exemplified by the EPPA and the USREP, and the results suggest that the TD-only approach is not robust with respect to key parameters (those are a priori unknown and highly uncertain). Villasana (2015) coupled the MIT EPPA model with the new Renewables Integration and Storage Assessment (RISA) model, a power generation expansion planning model for Mexico in which the hourly load profiles are incorporated, in order to analyze the value of storage under large-scale penetration of renewable energy in regards to climate policy.

3 Concluding remarks

Energy-economy modeling has been arousing interest among researchers and policy makers for nearly half a century. This chapter focuses on energy-economy modeling efforts with a specific emphasis on the decades-long debate about two main approaches in this field, top-down and bottom-up, and scrutinizes their characteristics, advantages, and shortcomings while referring to the seminal efforts as well as significant studies for each modeling framework. More importantly, hybrid modeling approaches, which couple the two modeling frameworks to benefit from the strengths of each, are elaborated with particular attention to the existing state-of-the-art models. Energy policies and critical issues related to the latest developments in advanced energy technologies (e.g. energy storage, renewable energy generation, intermittency of renewable resources), environmental impacts of increasing energy use such as global warming, penetration of new technologies such as electric vehicles into the market, and changes in consumer behaviors in line with the developments in information and communication technologies need to be analyzed in a consistent framework that is able to capture the details of the discrete nature of technologies as well as economic theory. Thus, efforts towards hybrid modeling become even more important on top of the theoretical and practical efforts summarized in this chapter.

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