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Integrated technological-economic modeling platform for energy and climate policy analysis

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ABSTRACT

CGE (computable general equilibrium) and bottom-up models each have unique strengths and weakness in evaluating energy and climate policies. This paper describes the development of an integrated technological, economic modeling platform (HYBTEP), built through the soft-link between the bottom-up TIMES (The Integrated MARKAL-EFOM system) and the CGE GEM-E3 models. HYBTEP combines cost minimizing energy technology choices with macroeconomic responses, which is essential for energy-climate policy assessment. HYBTEP advances on other hybrid tools by assuming 'full-form' models, integrating detailed and extensive technology data with disaggregated economic structure, and 'full-link', i.e., covering all economic sectors. Using Portugal as a case study, we examine three scenarios: (i) the current energy-climate policy, (ii) a CO_2 tax, and (iii) renewable energy subsidy, with the objective of assessing the advantages of HYBTEP vis-à-vis bottom-up approach. Results show that the economic framework in HYBTEP partially offsets the increase or decrease in energy costs from the policy scenarios, while TIMES is very sensitive to energy services-price elasticities, setting a wide range of results. HYBTEP allows the computation of the economic impacts of policies in a technological detailed environment. The hybrid platform increases transparency of policy analysis by making explicit the mechanisms through which energy demand evolves, resulting in high confidence for decision-making.

1. Introduction

Energy-economic-environmental models have been widely applied to support energy and climate policies, helping to explore and plan alternative energy futures and carbon mitigation strategies. Bottom-up (BU) and top-down (TD) models are the two main modeling approaches used, differing essentially in the technological detail and endogenous market adjustments [1]. The terms "bottom-up" and "top-down" are shorthand for disaggregated, technological energy systems models and aggregate economic models, respectively [2].

BU models focus on the energy system, characterizing it with great technological detail, including technical and economic information (e.g., efficiency, lifetime, investment and operation and maintenance costs). They are typically cast as optimization problems [1], defining the cost minimizing set of technologies needed to meet a given level of demand for energy services. Because BU models ignore that emergent technologies have greater financial risk, or may not be perfect substitutes to consumers, they do not provide a realistic microeconomic framework [3]. Moreover, they neglect interactions among the energy system and the rest of the economy. To accommodate responses to prices change, these models allow for energy service demand adjustments through energy service-price elasticities. Some authors (e.g., Refs. [4,5]) argue that this response captures part of the feedback effects between the energy system and the economy. Good estimates of energy services-price elasticities are rare, however, as the econometric literature centers mostly on energy demand [6].

Conventional TD models focus on the economy as a whole, disaggregating it in production sectors and consumption categories. The TD approach has been dominated by computable general equilibrium (CGE) models [7] which compute the levels of supply, demand and price that support the equilibrium across all the markets (e.g., capital, labor, materials/services). CGE models have an explicit representation of the microeconomic behavior of the economic agents (e.g., households, firms and government), however, the energy sector is represented by aggregated production functions, capturing substitution possibilities between input factors and energy forms through substitution elasticities [1]. These are usually estimated from historical data, with no guarantee that

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they will remain valid in the future [8]. CGE models enjoy widespread use in evaluating market based energy and environmental policy instruments, such as, energy or carbon taxes. Yet, due to the lack of detailed technology information, they have proven ineffective in assessing technology policies, while violations of energy and matter conservation principles may occur [9].

Decision makers need clear and consistent information concerning the impact of energy and climate policies in the economy, as well as the cost-effective technology portfolio to achieve their goals. Historical use of CGE and BU models has not adequately address these various policy dimensions. Hybrid models, that combine the two approaches, have been developed, with the objective of providing an integrated modeling framework: technologically explicit, with strong microeconomic foundations and macroeconomic closure [7].

Hybrid models can be classified according to their different approaches to integration. One method is a 'soft-link' between two independent TD and BU models, exchanging data and solving them iteratively until the two models converge (e.g., Refs. [10,11]). This approach has the advantage of being a transparent process and allows the use of complete models, as its computational complexity and running times are generally manageable [12]. However, due to the heterogeneity of the models, it may be difficult to achieve consistency and convergence [9]. Although some soft-linking processes have been implemented, they are mostly done through a single sector alone, e.g., transport [13], residential [14], electricity [12], thereby lacking in a full macroeconomic feedback over the range of technological choices for the entire energy system.

Another approach is linking one model to a reduced form of the other. The most common development is to couple a simple macroeconomic sector, producing a single non-energy good, to a BU model (e.g., Refs. [15–19]). Although this method includes energy—economy interactions, its high aggregation limits its usefulness in assessing sector-specific effects.

A third approach combines BU and TD models in a Mixed Complementarity Problem (MCP) format (e.g., Refs. [1,20–23]), introducing BU technological detail (commonly discrete electricity generation technologies) into a CGE framework. Its complexity and dimensionality, however, restricts the introduction of an extensive set of technologies, limiting the analysis of technology-oriented policies. Böhringer and Rutherford [9] have further outlined a method to decompose and solve iteratively MCP model, overcoming dimensionality issues (Refs. [24,25] applied this method using just electricity generation BU models).

Despite the extensive literature on hybrid models, there are few quantitative examples employing a 'full-link' (i.e., not focusing on only one sector) and 'full-form' BU and TD approaches (i.e., extensive technology data and disaggregated economic structure). This paper proposes a 'full-link' and a 'full-form' hybrid model, supported by an integrated methodology to soft-link the extensively applied BU TIMES model, developed by Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency[1] (IEA), with the CGE GEM-E3 model, used by several Directorates General of the European Commission.[2]

The hybrid platform, hereafter named HYBTEP (Hybrid Technological-Economic Platform) overcomes the main limitation of CGE models – failure in represent technology choices – by considering the energy profile and prices computed by TIMES (The Integrated MARKAL-EFOM system), which are sustained by a detailed technology database. It contains (current and emergent) technologies per sector, considering its characteristics and specificities. To minimize the drawback of bottom-up modeling – failure to represent adequately the link between energy and the economy – the changes in the sectors economic behavior are set by GEM-E3. According to the energy consumption profile and costs defined by TIMES, the CGE model defines the changes in the sectors' production functions, including the input of labor and materials.

HYBTEP allows each sector to respond differently to the energy-climate policies according to the cost-effective technology portfolio available and its sector-specific economic environment (e.g., interdependency in terms of intermediate consumption and distinct substitution and demand elasticities).

HYBTEP is applied to the Portuguese case, defined by the single country versions of the two models: TIMES_PT and GEM-E3_PT. Currently concerns about economic growth and high levels of public indebtedness are at the forefront of the Portuguese political discussion. At the same time, as a member of the European Union (EU), Portugal is subject to demanding energy and climate policy goals, which cannot be dismissed. In the last decades significant changes in the national energy system have taken place, namely the increase of electricity generation from renewable sources. Still Portugal is highly dependent on imported fossil fuels, which corresponds to two-thirds of its primary energy consumption [26]. This is reflected in its energy and carbon intensity (measured per unit of GDP (gross domestic product)), which are above the EU28 average, revealing lower productivity and indicating that there is potential to improve energy efficiency and decarbonize the economy [27,28]. This highlights how important it is for Portugal to integrate energy and economic concerns in comprehensive framework, assessing the impacts of energy-climate policies on both the energy system and the economy, making the country a relevant case study.

This paper presents a detailed description of the HYBTEP modeling framework and its application in three policy scenarios. The objective is to provide insights on the advantages of HYBTEP in assessing the impact of climate and energy policies on the energy system and the economy, and in defining mitigation strategies, when compared with conventional BU models. Thus, HYBTEP results are compared with TIMES outcomes considering different values for energy service-price elasticities, evaluating the performance of the modeling tools under each policy scenario.

The remainder of the paper is organized as follows: Section 2 describes TIMES and GEM-E3, and the linking methodology to build HYBTEP. Section 3 presents the calibration procedure between the models and outlines the assumptions under each policy scenario. Section 4 investigates the impact of the policy scenarios on the energy system, greenhouse gas (GHG) emissions and the economy, allowing for a comparison between HYBTEP and TIMES outcomes. Section 5 concludes and evaluates the strengths and weakness of the hybrid approach in the assessment of energy and climate mitigation policies.

2. Methodology

This section presents a characterization of the two models connected in HYBTEP modeling framework, as well as a description of the soft-link methodology.

2.1. TIMES model

TIMES (The Integrated MARKAL-EFOM system) is an intertemporal linear programming energy model generator. In its partial equilibrium formulation, the objective of TIMES is to minimize total energy system cost to satisfy energy services demand, i.e., maximization of the total net surplus, subject to technological,

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[1] See http://www.iea-etsap.org/web/Applications.asp for a list of TIMES applications and respective publications.

[2] See http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/gem-e3/publications.cfm for a list of GEM-E3 applications and respective publications.