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# A sequential approach to integrated energy modeling in South Africa

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## HIGHLIGHTS

- We develop an integrated approach to energy sector and economywide modeling.
- Exploitation of regional hydropower potential at scale is analyzed.
- A regional energy strategy, anchored in hydropower, represents a potentially attractive option.

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## ABSTRACT

We develop a sequential approach to link a bottom-up energy sector model to a detailed dynamic general equilibrium model of South Africa. The approach is designed to simultaneously address the shortcomings and maintain the attractive features of detailed energy sector and general equilibrium models. It also reflects common country-level energy planning processes. We illustrate the capabilities of this integrated bottom-up approach by analyzing the implications of (i) a carbon tax, (ii) liberalization of import supply restrictions in order to exploit regional hydropower potential, and (iii) a combined policy where both carbon taxes and import liberalization are pursued. For the combined scenario, our results suggest substantial emissions reductions relative to Baseline at essentially no cost to economic growth but about a one percent reduction in employment. We conclude that a regional energy strategy, anchored in hydropower, represents a potentially inexpensive approach to decarbonizing the South African economy. The strategy also has political economy attractions in that the combined approach reduces the burden of adjustment of politically sensitive sectors.



## 1. Introduction

The availability of sufficient energy is vital for economic development. This was recently illustrated in South Africa, where widespread electricity shortages constrained economic activity [1] and prompted the government to propose a new long-term energy investment plan [2]. At the same time, South Africa committed itself to reducing its greenhouse gas emissions, half of which are from electricity generation [3]. However, investing in new and cleaner energy can incur significant trade-offs, most obviously in the form of higher energy prices. This may lead to slower economic growth, job losses and a higher cost-of-living for low-income households, which are three major policy concerns for South Africa [4]. As such, investment plans, particularly in developing countries, need to not only meet future energy needs and environmental commitments, but also minimize socioeconomic trade-offs.

Standard practice in energy planning is to use detailed bottom-up energy sector models. A shortcoming of this approach, however, is that it fails to take into account the demand response of proposed energy paths and therefore only provides a rough estimate of the optimal build-plan. Another approach is to combine an energy sector model with a computable general equilibrium (CGE) model that can measure demand responses. However, full inter-temporal integration usually constrains the level of detail in general equilibrium models, thus limiting their usefulness for policy analysis, including measuring how energy prices affect socioeconomic outcomes, such as employment and incomes.

This paper presents an iterative modeling approach to energy planning that addresses these shortcomings while maintaining the attractive features of detailed energy sector and general equilibrium models. The paper focuses on electricity planning in

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South Africa. Section 2 presents a sequential dynamic approach that extends existing studies that typically opt for full optimization at the cost of using lower-resolution economic models. Section 3 illustrates the usefulness of this approach by examining two energy-related policies under consideration in South Africa, i.e., carbon taxes and the removal of electricity import quotas. The final section concludes by drawing lessons for South Africa.

## 2. Methodology

We follow the methodology proposed by Lanz and Rausch [5], i.e., an integrated bottom-up energy sector and general equilibrium model. The authors show that this approach allows for the combination of model strengths that enable the assessment of policy changes on energy prices, demand and welfare as well as the identification of possible abatement opportunities. They find this methodology to be superior to independent partial equilibrium models, which fail to account for the secondary impacts of shocks. It is also superior to independent general equilibrium models, which do not accurately capture changes in fuel substitution because of their lack of detailed energy technology information. Various studies adopt the integrated bottom-up approach (see, for example [6,7]).

We differ from existing studies in that we link the energy sector and general equilibrium models via a sequential or recursive dynamic process. By avoiding using forward-looking inter-temporal dynamics in the general equilibrium model, it is possible to retain a higher resolution depiction of the economy that is more useful for simulating policies and measuring socio-economic outcomes. Since both models appear in the literature, we briefly describe their main characteristics before discussing model integration and convergence.

### 2.1. Energy sector model

We use the South African TIMES Model (SATIM), which is a country-specific application of The Integrated MARKAL-EFOM System (TIMES). SATIM is an inter-temporal bottom-up partial equilibrium optimization model of South Africa's energy sector (see [8]). In the full version of SATIM, demand is for "useful energy", e.g., demand for energy services like cooking, lighting and heating. Final energy demand is calculated endogenously based on the optimal mix of technologies. This allows for trade-offs between demand and supply sectors, and explicitly captures process changes, fuel and mode switching, and technical or efficiency improvements.

The version of SATIM used in this study includes only the power sector module. It computes the least-cost power plant mix, both in terms of capacity and production, over a defined planning horizon. This is derived from an optimization problem, where the objective function is to minimize the discounted future capital and operating costs of power plants. SATIM uses linear or mixed integer programming to solve the least-cost planning problem subject to a series of constraints and system parameters. Constraints include future electricity demand; required reserve margins; and resource limits (e.g., fossil reserves and renewable energy potential). System parameters include load curves; fuel prices and availability; the existing stock of power plants (i.e., efficiencies, running costs and retirement profiles); and new power plant options (i.e., investment costs, capacity factors and construction times). Appendix A discusses the data sources and assumed values for key price and cost parameters in the model.

SATIM permits simulation of South Africa's main energy policies choices. To illustrate the functionality of the integrated modeling framework, we focus on two. First, SATIM can impose restrictions on imported electricity – currently set at 15% of total system capacity. This may become a binding constraint on the power plant mix given the considerable potential for neighboring countries to supply hydropower and coal-fired electricity to the South African market via the Southern African Power Pool (i.e., an integrated regional network of transmission infrastructure). Secondly, SATIM can incorporate carbon taxes on GHG emissions via changes in fossil fuel prices. Detailed assumptions on technology costs are given in Appendix A.

### 2.2. Economic model

We use the South African General Equilibrium (SAGE) model, which is a recursive dynamic country-level, economywide model. This is a dynamic variant of the generic static model described in Lofgren et al. [9] and is a descendant of the class of computable general equilibrium (CGE) models introduced by Dervis et al. [10]. The core structure and dynamics of the SAGE model are described in Diao and Thurlow [11].

SAGE simulates the functioning of the South African economy and provides useful insights on the direct and indirect linkages that connect different groups of profit-maximizing industries and utility-maximizing households, as well as the government and the rest of the world. SAGE provides a detailed and comprehensive representation of the economy, including 62 industries, 49 products, 9 factors of production, and 14 representative household groups. This information is drawn from a 2007 version of the Social Accounting Matrix described in Davies and Thurlow [12], and was reconciled with the 2007 Energy Balance [13]. As seen in Fig. 1, SAGE's energy sector comprises nine electricity and four fuel production technologies.

SAGE's recursive dynamic structure consists of within- and between-period components. Within each time period, SAGE is solved subject to given levels of population, productivity and capital supply. One important feature of SAGE is that non-energy industries can respond to rising energy prices by investing in less energy-intensive technologies, subject to investment financing constraints (see Alton et al. [14]). Between periods, SAGE is updated to reflect population growth, technical change and capital accumulation. The latter is determined endogenously based on previous period investment levels. New capital is allocated to sectors based on their relative profit rates. Once invested, capital becomes sector-specific. This specification partly captures the adjustment costs from reorienting production across industries of different energy- and carbon-intensities. All new power plant investments are financed through a regulated electricity tariff that amortizes the debt and covers the operating and maintenance costs incurred by South Africa's electricity provider, ESKOM, which is an independently managed state enterprise. Finally, at the macroeconomic level, we assume that nominal private and public consumption and investment spending are fixed proportions of total absorption, and that the exchange rate adjusts to maintain an exogenously-determined current account balance.

### 2.3. Model integration

We formally link the SATIM and SAGE models in a way that retains the best features of both models, i.e., one that captures detailed energy investment options, as well as detailed information on economic structure and behavior. Within our linked framework, SATIM computes an optimal power plant investment plan based on forecasted electricity demand and fossil fuel prices from SAGE. SAGE replicates the power plant mix and associated electricity price from SATIM, and then revises its electricity demand and fuel price forecasts.