Energy 61 (2013) 479–490

Contents lists available at ScienceDirect

Energy

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

Model evaluation and hindcasting: An experiment with an integrated assessment model

Vaibhav Chaturvedi*, Sonny Kim, Steven J. Smith, Leon Clarke, Zhou Yuyu, Page Kyle, Pralit Patel

Joint Global Change Research Institute, College Park, MD, USA

ARTICLE INFO

Article history:
Received 5 April 2013
Received in revised form
26 July 2013
Accepted 30 August 2013
Available online 8 October 2013

Keywords:
Integrated assessment modeling
Evaluation and hindcasting
GCAM (Global Change Assessment Model)
Building sector energy
USA

ABSTRACT

Integrated assessment models have been extensively used to examine long term energy and greenhouse emissions trajectories, but these models have rarely been examined with respect to their ability to capture historical dynamics. We evaluate the USA buildings component of the Global Change Assessment Model by calibrating the model for 1990 and running forward to 2095. Results for 1995, 2000, 2005 and 2010 are compared to historical estimates at the level of fuel, service, and US states. We highlight that the creation of a historical evaluation dataset is one of the foremost challenges in the evaluation process. This model set-up matches the reported growth of residential floorspace but slightly overestimates heating service demand and underestimates the growth in miscellaneous plug loads. While cooling service appears to be underestimated in 2005, we find little evidence for a systematic bias for other years. The apparently rapid growth of some demands in the commercial sector was also not captured. While these differences carry through into future projections, the overall character of these projections is not changed. These results highlight the difficulty of determining the relationship between energy service demand, which is an unobserved variable, and its drivers when there is limited historical data.

1. Introduction

Integrated assessment modeling has been extensively used as a tool for analyzing policies and strategies for mitigating greenhouse gas and local pollutant emissions [1–16]. Numerous IAMs (integrated assessment models) have been developed for improving our understanding of the evolution of economic development pathways, energy consumption trajectories, policy options, and the consequent impacts on environment [17].

Different integrated assessment and energy-economy models present widely varying future pathways of energy consumption and emissions [18,19] with the range of energy consumption varying by a factor of two even by 2020 [20]. There are two reasons for such divergence: input assumptions and model structural differences. Models use different assumption about income, growth, population growth, and technology. Models also differ in an enormous number of ways, including spatial, temporal, and process-level resolution, solution algorithms, methods for tracking capital stocks, economic feedbacks, and technology representations [18,20,21].

Though IAMs have robust theoretical foundations in economics as well as physical sciences, how well these would be able to project historical evolution trajectories of energy and emissions is still an unanswered question. Uncertainty in the future evolution of economies and technologies will follow-through to estimates of future energy consumption and emissions. One method of gaining insight into the future evolution of energy and emissions is to analyze a suite of scenarios from a number of different models. This approach allows some exploration of structural uncertainty, but it is generally difficult to coordinate more than a small set of input assumptions, such as climate policy or perhaps population, GDP (gross domestic product), or fossil resources. This means that these comparisons across scenarios incorporate variations in both input assumptions as well as structural differences.

Examining how well a model can simulate historical behavior requires a hindcast exercise, in which a model is run over a historical period, using historical data as input, and then comparing outputs to historical data. In this paper, we undertake an initial hindcast experiment using the GCAM (Global Change Assessment Model). We use the regional version of GCAM, wherein the United States of America (USA) residential and commercial building sector is disaggregated into 50 states and the District of Columbia. We calibrate GCAM for the year 1990 and then run till 2095 with five

* Corresponding author. Tel.: +1 301 405 0898.
E-mail addresses: vaibhav.chaturvedi@ceew.in, vaibhavc@iimahd.ernet.in (V. Chaturvedi).

0360-5442/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.energy.2013.08.061

year time steps, using the same projection parameter settings (e.g., those controlling demand and price response and technology choices) as used for the standard projections. This results in four years of simulation output, e.g., 1995, 2000, 2005 and 2010, that can be compared against historical data.

The first contribution of this work is to provide feedback on the approach to modeling the buildings sector in GCAM, and perhaps other models. Indeed, the exercise has highlighted several avenues for potential improvements in GCAM. This exercise also constitutes one of the first efforts to run a higher-resolution integrated assessment model over a historical period as a hindcasting experiment. This allows us to examine the issues that are raised by such experiments, which are relevant to the broader modeling community if hindcasting were to be included more commonly in the future as a form of model evaluation.

Perhaps the most prominent issue that arises is the substantial, and also spatially and temporally heterogeneous, datasets required. Limitations in historical data can provide challenges in terms of a meaningful estimate of historical experience against which to compare hindcast outputs.

The importance of using a modeling framework for this exercise should be noted here. In contrast to the exercise in this paper, it would be possible to test the equation structure for the buildings sector in GCAM by isolating those equations, assuming exogenous factors for prices and other variables that provide the interactions between sectors, and then comparing to historical results. This is undoubtedly a valuable exercise, and it is one that has been implemented, at lest informally, by integrated assessment teams to develop key parameters. van Ruijven et al. [22] have conducted a formal parameter sensitivity analysis for the global buildings sector, comparing model results with historical data for building sector energy consumption. Here we conduct an experiment running a full integrated assessment model, with a focus on the buildings sector, including detailed data on building energy services available for the United States. It will be this full exercise that will ultimately be important for understanding how effectively models can represent aggregate phenomenon such as global energy consumption or global GHG (greenhouse gas) emissions. Further, by running the full model, we can explore the evolution of interacting forces such as energy prices that are heavily influenced by other sectors in the model.

A further objective of this effort is to use this experiment as a means to understand and highlight the issues involved in the process of evaluating a long term integrated assessment or energy model, and our results and discussions should be understood in this perspective. We present our research as an initial step in the broad objective of evaluating long-term models, understanding their limitations, and improving their capabilities.

Section 2 below focuses on our method and presents our model GCAM and the process of evaluation we undertake in this research. Section 3, addresses the issue of creating an evaluation dataset. Section 4 presents the result from this experiment focusing on the historical years but still presenting insights about the long run. We focus on the results for residential sector at the national and state level, but also highlight interesting issues for the commercial sector. We conclude with insights for the process of model evaluation in Section 5.

2. Method

2.1. Overview of the global change assessment model

The 50-state building model in this study is embedded in the GCAM global integrated assessment model. GCAM has been extensively used for global and regional energy and climate policy scenario analysis [8,11,16,23–27]. GCAM is a dynamic-recursive model, which combines partial equilibrium economic models of the global energy system [6] and global agriculture and land use including forestry and biomass energy crops [28]. Atmosperic gas-cycles and global climate is simulated with the MAGICC (Model for the Assessment of Greenhouse-Gas Induced Climate Change) [29]. GCAM represents global and regional supplies and demands of energy and agricultural products across 14 different geopolitical regions in a partial equilibrium economic framework. The buildings sector is one of the three end-use sectors (buildings, industrial, and transportation) for which the model produces and transforms energy in an integrated framework. The model is solved by finding a set of prices in all markets at which supplies match demands. For this study, GCAM is run on five-year time periods from 1990 (calibration year) to 2095.

The next section provides an overview of the 50-state buildings model in GCAM.

2.2. Overview of 50-state buildings model in GCAM

Details for the 50-state building model in GCAM can be found in Ref. [30]. End use demands for a representative residential and commercial in each state are modeled for a variety of energy services: space heating, space cooling, lighting, cooking, hot water, appliances, other appliances, office equipment, commercial refrigeration and ventilation (Fig. 1). A portfolio of fuels-gas, electricity, oil, coal and biomass and associated technologies are available to meet these end use service demands. The regional US building version is nested within the global GCAM.

In GCAM, energy demand for the both residential and commercial building sector is estimated using the following equation

$$\text{Energy}_i = \text{population}\cdot\left(\frac{\text{floorspace}}{\text{population}}\right)\cdot\sum_t\left(\frac{\text{service}_{i,t}}{\text{floorspace}}\right)\Big/\text{efficiency}_{i,t} \tag{1}$$

where subscript 'i' stands for service (e.g. heating) and 't' implies technology for a given service (e.g. gas furnace for heating). Two portions of equation (1), the projection of floorspace per capita and the estimation of service demand per unit floorspace, are described below.

For estimating future growth in floorspace, we make a simple assumption that demand for floorspace increases with income but at a decreasing rate. The growth rate in floorspace demand declines as income increases and as demand approaches exogenously specified levels.

$$f = (f_{\max} - f_{\min})\left[1 - \exp\left(-\frac{i}{\mu_f}\right)\right] + f_{\min} \tag{2}$$

where $f_{\max}$ is the assumed asymptote of per capita floorspace, $f_{\min}$ is the assumed level for minimum floorspace, i is per capita income,