Technological Forecasting & Social Change 105 (2016) 215–223

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Bounding US electricity demand in 2050

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ARTICLE INFO

Article history:
Received 25 June 2015
Accepted 1 September 2015
Available online 17 February 2016

Keywords:
Bounding analysis
Long-term projection
Energy demand
Electricity demand
Climate change

ABSTRACT

Limiting climate change requires a radical shift in energy supply and use. Because of time lags in capital investments, the political process, and the climate system, potential developments decades from now must be considered for energy policy decisions today. Traditionally, scenario analysis and forecasting are used to conceptualize the future; however, past energy demand forecasts have performed poorly displaying overconfidence, or a tendency to overly discount the tails of a distribution of possibilities under uncertainty. This study demonstrates a simple analytical approach to bound US electricity demand in 2050. Long-term electricity demand is parsed into two terms — an expected, or "business-as-usual," term and a "new demand" term estimated explicitly to account for possible technological changes in response to climate change. Under a variety of aggressive adaptation and mitigation conditions, low or high growth in GDP, and modest or substantial improvements in energy intensity, US electricity demand could be as little as 3100 TWh or as much as 17,000 TWh in 2050. Electrification of the US transportation sector could introduce the largest share of new electricity demand. Projections for expected electricity demand are most sensitive to assumptions about the rate of reduction of US electricity intensity per unit GDP.

1. Introduction

Past efforts to project future US electricity or overall energy consumption over long time horizons (i.e. multiple decades) have been remarkably unsuccessful. Even when projections have included uncertainty bounds, these bounds have often failed to include the values that were ultimately realized (Greenberger, 1983; Shlyakhter et al., 1994; Smil, 2003). Although more recent mid-term US energy demand projections from the Energy Information Administration (EIA) have smaller errors of approximately 4% (projections with lead times of 10–13 years), these hide much larger errors for projecting the drivers of energy demand, which at least in recent years, have tended to offset each other (O'Neill and Desai, 2005). However, analysts intent on examining a range of issues, including the implications of future climate change, need plausible and unbiased projections as inputs to their work.

There are a variety of analytical approaches for characterizing the future. Carter et al. (2007) have reviewed many of them. Three approaches are relevant to this paper: (1) scenarios and storylines, (2) projections, and (3) artificial experiments. Carter et al. (2007) contrast these according to their comprehensiveness, or degree to which the characterization captures details of the socioeconomic system being represented, and their plausibility, or whether the characterization is deemed possible.

For long-term global projections of greenhouse gas emissions due to energy demand and land use, the Intergovernmental Panel on Climate Change (IPCC) commissioned a *Special Report on Emissions Scenarios* (SRES) (Nakicenovic et al., 2000). The range of scenarios featured in the SRES were based on detailed story lines, which made them highly comprehensive and plausible. However, much of the detail in these story lines was never used in subsequent assessment activity, and a number of scenarios that were at least as internally consistent and plausible as those presented were not developed nor used (Schweizer and Kriegler, 2012). Morgan and Keith (2008) have provided a detailed critique of such scenario methods, arguing further that the use of a few detailed storylines may cause users to ignore other possible futures as a result of a cognitive bias known as "availability," which can result in systematically overconfident projections (Dawes, 1988). Lloyd and Schweizer (2014) have also argued that intuitively derived storylines are inappropriate for scientific assessments due to their demonstrably low levels of objectivity in comparison to other methods.

In our view, this recent critical scholarship raises questions about the usefulness of scenarios and storylines for long-term energy demand projections. Instead, Morgan and Keith (2008) as well as Casman et al. (1999) suggest that when uncertainty is high, simple bounding analysis may offer a more useful analytical strategy. Lloyd and Schweizer (2014) clarify that the improvement of an approach such as bounding analysis is rooted in enhancing *unbiased* objectivity; as such methods aim to correct the cognitive bias of availability. According to the typology of Carter et al. (2007) bounding analysis would be a type of projection that is less comprehensive than a scenario. In general, projections may be just as plausible as scenarios; however, bounding analysis also aims to improve the calibration of upper and lower bound estimates. This requires special attention to boundary cases, which makes bounding analysis more akin to an artificial experiment. Carter et al. (2007) note that

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http://dx.doi.org/10.1016/j.techfore.2015.09.001
0040-1625/

artificial experiments may test the limits of plausibility and, as a result, may not be as plausible as scenarios. Nevertheless, they are a legitimate characterization of the future and follow “a coherent logic in order to study a process or communicate an insight” (Carter et al., 2007).

In disciplines such as physics, natural science, and engineering, it is common practice to engage in order of magnitude reasoning and bounding analysis. For example in the area of nuclear engineering, materials and waste management, a series of studies have used order-of-magnitude arguments to set bounds on possible future outcomes (Lewis et al., 1979; Hora and Iman, 1986; Brandwajn and Lauby, 1989; Bess, 1994; Chandler, 2001; Karditsas and Loughlin, 2001; Trabalka and Kocher, 2007; Ferson, 2006; Sentz and Ferson, 2011). However, such methods are far less common in areas such as economics, public health or environmental science, and when applied, they have often invoked considerable controversy (Morgan, 2001; Ha-Duong et al., 2004; Greenland, 2004; Casman et al., 2004).

In 1988, John Harte, a Professor in the Department of Environmental Science, Policy, and Management, at the University of California Berkeley, became sufficiently concerned about educating his students in order-of-magnitude and related methods that he wrote the classic book *Consider a Spherical Cow: A Course in Environmental Problem Solving* (Harte, 1988) in order to illustrate how a range of such methods can be applied to environmental problems. Similarly, in his tutorial text *Turning Numbers into Knowledge: Mastering the Art of Problem Solving*, Koomey (2008) wrote, “When you've set up your calculation with your best guesses for the various parameters, it's often instructive to identify those that are least certain and determine a plausible range for them. You then carry through the calculation using the upper and lower ends of the ranges for all the inputs.”

In this paper, we perform such an analysis to bound the plausible range of US electricity demand in the year 2050. The insights we aim to communicate are that plausible new electricity demands, which could be motivated by adaptation to climate change or mitigation policy, may be substantially underestimated in traditional energy demand forecasts (e.g. the *Annual Energy Outlook* published by EIA). An undesirable result of underestimates is that they may artificially constrain the policy recommendations provided by studies.

2. Method

We begin by decomposing the problem using the simple identity:

$$E = G \times (E/G) = Ge \tag{1}$$

in which G is gross domestic product (GDP) and E represents energy use. The quantity e is defined by the ratio for energy intensity of the economy (E/G). Readers familiar with the Kaya Identity (Kaya, 1990) may recognize Eq. (1) as a subset of the larger identity used to characterize energy-related greenhouse gas emissions. It should be noted that Eq. (1) subsumes future population growth in the projection of the size of GDP.

As outlined below, we can use historical time series to develop an understanding of how G(t) and ($E(t)/G(t)$) have evolved in the past. By choosing low and high values from those time series and similar studies we define expected, or “business as usual,” projections $G_{\text{BASE\_LO}}(t)$ and $G_{\text{BASE\_HI}}(t)$ and then construct:

$$\begin{aligned} E_{\text{LO}}(t) &= E_{\text{BASE\_LO}}(t) + E_{\text{NEW\_LO}}(t) \\ &= (G_{\text{BASE\_LO}}(t))(e_{\text{BASE\_LO}}(t)) + E_{\text{NEW\_LO}}(t) \end{aligned} \tag{2}$$

$$\begin{aligned} E_{\text{HI}}(t) &= E_{\text{BASE\_HI}}(t) + E_{\text{NEW\_HI}}(t) \\ &= (G_{\text{BASE\_HI}}(t))(e_{\text{BASE\_HI}}(t)) + E_{\text{NEW\_HI}}(t) \end{aligned} \tag{3}$$

which we evaluate in the year 2050. In this case, $E_{\text{NEW\_LO}}(t = 2050)$ sums the impact on electricity demand of all the developments that by 2050 might cause electric demand to be even lower than the low projection, $E_{\text{BASE\_LO}}(t = 2050)$. Similarly $E_{\text{NEW\_HI}}(t = 2050)$ sums the impact on electricity demand of all the developments that by 2050 might have caused electric demand to be even higher than a high projection, $E_{\text{BASE\_HI}}\ (t = 2050)$.

2.1. Projecting low and high baselines for electric energy use

In order to construct the baseline projections of possible future US electricity demand, we consider time series in past GDP growth and electricity intensity (kWh/GDP). We focused on the time period 1949–2007 for two reasons. First, this is a multi-decadal period of approximately the same duration as our projection through 2050. Second, it includes disruptions such as the energy crises of the 1970s and shows long-term trends that persist nevertheless. On this note, although the US economy has experienced a serious recession and undergone corrections since 2008, it remains unclear what the long-term impact of these near-term disruptions will be. It is possible that the US economy will return to pre-recession rates of growth (in which case the recent discontinuity in GDP would simply shift the growth curve down slightly).

Data collected from the US Bureau of Economic Analysis (2008) reveal that from 1949 to 2007, real US GDP grew exponentially, at an average of about 3.3%. However since about 1990, US GDP has grown more slowly than in previous decades at an average rate of 3.0%. These trends are summarized in Fig. 1. The *Annual Energy Outlook*, (Energy Information Administration (US), 2008) a series of energy demand projections published each year by the US Energy Information Administration, considers 25-year trends of average real US GDP growth as low as 1.8% in its low economic growth case.

We used these different values of real US GDP growth to construct a high baseline based on continued growth through 2050 at about 3.3% and a low baseline based on continued growth at 1.8%. Note that in constructing the low baseline, we do not consider major socio-economic disruptions such as depressions, wars, or pandemics.

We obtain a high and low estimate of electricity intensity (represented by the variable e in Eq. (1)) by examining the historical trend of the ratio of electricity generated to real GDP, which is shown in Fig. 2. This ratio can be thought of as a proxy for the efficiency with which the overall economy uses electricity. Since the mid-1970s, US electricity intensity has generally decreased. Considering the two time frames of decreasing e (1976–1987 and 1991–2007), the slopes

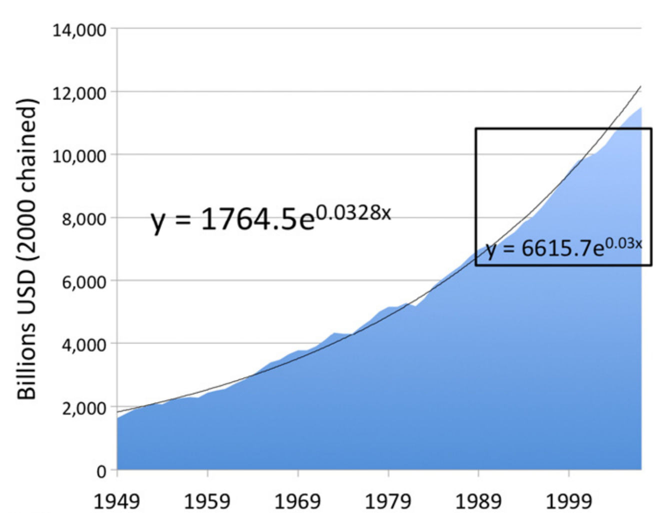

Fig. 1. Two possible curve fits for real long-term growth in US GDP. The main curve over the 1949–2007 period yields an annual growth rate of about 3.3%. Over the 1990–2007 period (boxed), US GDP growth is more modest at 3%. Source data are from the US Bureau of Economic Analysis (2008).