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Bounding US electricity demand in 2050

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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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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

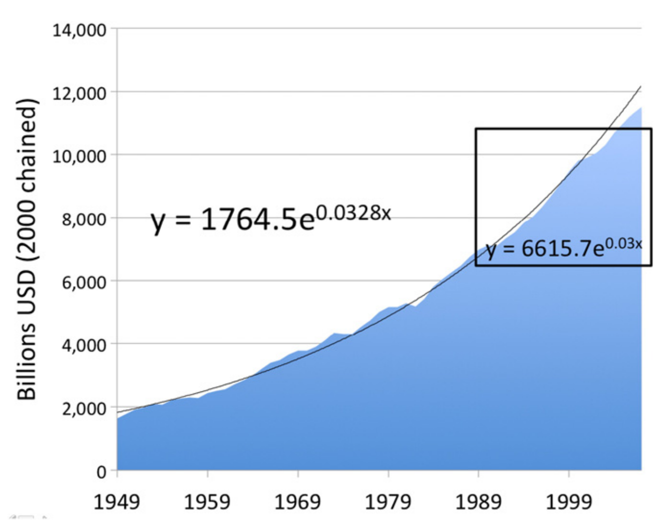

Fig. 1. Two possible curve fits for real long-term growth in US GDP. The main curve over the 1949–2007 period yields an annual growth rate of about 3.3%. Over the 1990–2007 period (boxed), US GDP growth is more modest at 3%. Source data are from the US Bureau of Economic Analysis (2008).

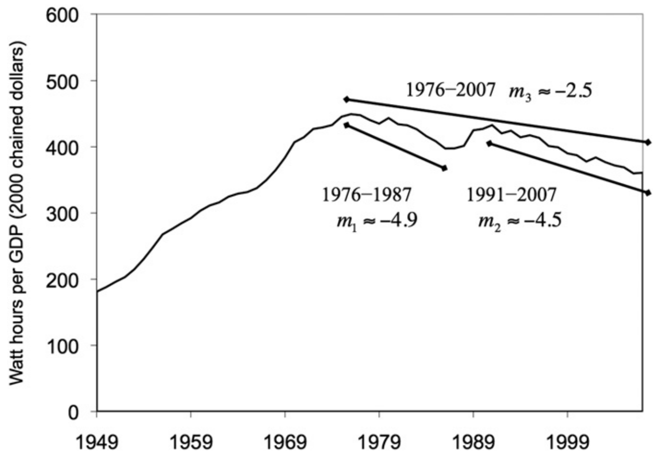

Fig. 2. Mid-term trends in decreasing aggregate electricity intensity for the US economy over three periods, 1976–1987, 1991–2007, and 1976–2007. Source data are from the US Energy Information Administration and Bureau of Economic Analysis (Bureau of Economic Analysis (US), 2008; Energy Information Administration (US), 2009).

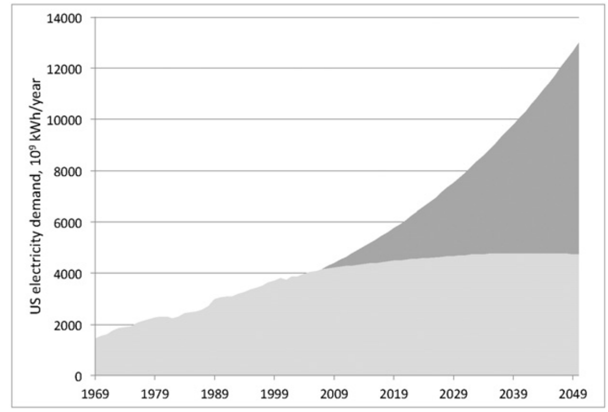

Fig. 3. The upper- and lower-case baselines for US electricity demand in 2050 obtained by combining high and low projections of GDP growth with high and low projections of the electricity intensity of the US economy. Electricity demand for the upper baseline approaches 13,000 TWh in 2050, while the lower baseline falls to just under 5000 TWh.

of the ordinary-least-squares lines are similar representing an average decrease of about 5 Wh/$GDP per year. However, over the full 1976–2007 period, the average annual decrease in e has been much more modest — only 2.5 Wh/$GDP.

We construct out two baseline projections for possible future US electricity demand by combining the two GDP growth rates and these two rates for e. In constructing $E_{BASE\_LO}(t)$, e continues to decrease at 4.5 Wh/$GDP each year, while the economy grows at 1.8%. In $E_{BASE\_HI}(t)$, e continues to decrease at 2.5 Wh/$GDP, and the economy grows at 3.3%. By 2050 $E_{BASE\_HI}(t)$ has grown to nearly 13,000 TWh of total electricity demand by 2050, while $E_{BASE\_LO}(t)$ falls to just under 5000 TWh. The upper-case projection represents an increase over current electricity generation by about a factor of three, while the lower-case projection represents a slight increase.

It should be noted that certain assumptions are endogenized in these baseline projections. As stated previously, other variables from the Kaya Identity, such as population and GDP per capita growth, are subsumed into the GDP projection. This means that historical trends in US population growth (including fertility rates, immigration rates, life expectancy, and national distribution) are projected to continue through 2050. The same can be said of historical trends for GDP per capita. For the variables that are represented explicitly (GDP growth, electricity intensity of GDP), historical trends are similarly projected forward. This would include the structural shift in the US economy from manufacturing to services (as discussed by the Office of Energy Efficiency and Renewable Energy (Department of Energy (US), 2012)), as well as trends for the increase in plug loads in commercial and residential buildings to accommodate new electronic devices such as copiers, coffee machines, and personal computers (as found by the EIA (Energy Information Administration (US), 2011)). These are examples of how the baseline projection is less comprehensive than a scenario.

2.2. Possible technical and behavioral developments

By 2050, the high and low baselines sketched in Fig. 3 might be further affected by a range of technical and behavioral developments. We were particularly interested in changes that would be in response to climate change or might be motivated by mitigation policy. In discussion with colleagues, we developed and refined a list of such possible developments that might increase electricity demand to an upper bound above the upper baseline or lower electricity demand to a lower bound below the lower baseline. We excluded some on the grounds that their overall contribution to US demand would be modest (≤a few hundred TWh/year) in the context of this bounding effort. Table 1 lists the developments we have included in our assessment.

While the electricity savings of efficiency improvements for the built environment, consumer electronics, household appliances, and office equipment could be small individually when considered at the end-use level (less than or on the order of 100 TWh/year), their total impact could be substantial (Electric Power Research Institute, 2009a). Because our focus is on changes that affect electricity use rather than generation, we exclude considerations of changes in the efficiency of the power delivery system and in the electricity needed to operate emissions control systems at power plants.

Section 2.3 details how we estimated the developments summarized in the upper and lower boundary cases of Table 1. In many cases, we concluded that the most appropriate projections would be a function of explicit assumptions for future population. This decision could appear to pose a problem for the bounding analysis, as future trends for population growth are endogenized in the baseline projection as discussed in Section 2.1. However, it should be noted that the baseline projections reflect only a continuation of historical trends, where transportation, many industrial furnaces, and space and water heating in buildings all remain powered by fossil fuels. Additionally, the baseline projection assumes that climatic conditions through 2050 would be similar to what was observed since 1970. These particular assumptions are being investigated through the bounding analysis and should therefore be considered additional electricity demands that depart from the historical trend in the upper bound case. Similarly, for the lower bound case, we consider aggressive policy changes that would accelerate efficiency improvements beyond the historical trend.

2.3. Estimating new US electricity demands and savings in 2050

In this section, we briefly outline the order-of-magnitude estimates we have made of the possible contribution to electricity demand of each of the elements in Table 1.

2.3.1. Widespread use of plug-in hybrid electric vehicles

The 2001 National Household Travel Survey estimates the average age of a light-duty vehicle (LDV) in the US household fleet as 9 years (Hu and Reuscher, 2004). By 2050, most of the US LDV fleet will have turned over at least twice. For the upper bound analysis, we assumed that some combination of regulation and market forces results in 100% of the US LDV fleet converting to PHEVs by 2050. It was also assumed that the PHEV fleet would settle predominantly on one type of battery.

Table 1
Final set of possible developments by sector considered in this analysis that could comprise new US electricity demand in 2050.

	Increases electricity demand (upper bound case)	Decreases electricity demand (lower bound case)
Transportation	• Widespread use of plug-in hybrid electric vehicles	Does not occur
Industry	• Expanded use of electricity for process heating	Does not occur[a]
Residential	• Substantial increases in air conditioning • Widespread use of heat pumps for space and water heating	• Aggressive efficiency regulations for the residential sector including o Energy-efficient shells and lighting for new construction o Energy-efficient shells and lighting for renovations o Performance standards for electronics, appliances, and HVAC equipment
Commercial	• Substantial increases in air conditioning • Widespread use of heat pumps for space and water heating • Widespread use of desalination for public water supplies in the Southwest and Florida	• Aggressive efficiency regulations for commercial sector including ○ Energy-efficient shells and lighting for new construction ○ Energy-efficient shells and lighting for renovations ○ Performance standards for office and HVAC equipment

[a] Although machine drives currently comprise the bulk of industrial sector electricity demand, the Electric Power Research Institute (EPRI) estimates that the realistically achievable potential of efficiency improvements will approach the economic potential by 2030 (Electric Power Research Institute, 2009a). Since realistically achievable efficiency improvements are already endogenized in the bounding analysis, it would be redundant to estimate them separately.

For an upper bound estimate, we considered that the 2050 fleet of PHEVs may have longer-range (60 km, or 40 mile) batteries.[1]

We used historical data to construct a simple projection of LDV growth as a function of the US population (United States Department of Transportation, 2009). Projections of "plant to wheel" electricity demand of the PHEV fleet were based upon calculations performed by Samaras and Meisterling (2008). The 2050 fleet of PHEVs with longer-range batteries was estimated to require about 2500 TWh/year of electricity.

2.3.2. Substantial increases in air conditioning

By 2050, climate change might increase summertime temperatures sufficiently to drive substantial increases in air conditioning. To estimate changes in air conditioning demand, we required (a) projections of changes in summer temperatures for the US, and (b) projections of electricity demand that could be attributable to increased air conditioning in residential and commercial buildings. A description of our approach is below.

Projections for summer temperature change in the US by 2050 were obtained from the Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset developed by the World Climate Research Program (WCRP) (World Climate Research Programme Coupled Model Intercomparison Project phase 3 (WCRP CMIP3), 2010). Temperature projections were obtained at the Census division level. For the upper bound, only SRES A2 scenarios were considered, as this family covers the high range of global carbon dioxide emissions available in the database.[2] Using the IPCC A2 marker scenario as a benchmark, the radiative forcing of A2 scenarios may reach 8–9 W/m^2 (Meehl et al., 2007). For the lower bound, only B1 scenarios were considered, as the SRES B1 family covers the low range of global carbon dioxide emissions available in the database. Using the IPCC B1 marker scenario as a benchmark, the radiative forcing of B1 scenarios ranges from 4 to 5 W/m^2, which is about half of the radiative forcing of A2. For each scenario family, a subset of CMIP3 model projections was used to isolate the temperature signal of worst-case (i.e., high climate sensitivity) and best-case (low climate sensitivity) projections. The top and bottom five projections for average summer temperature by Census division were then averaged to obtain summer temperature changes that would be large (relevant for the upper bound of electricity demand) or small (relevant for the lower bound).

Periodic estimates for commercial building and residential air conditioning at the level of Census divisions are available from the EIA Commercial Building Energy Consumption Survey, or CBECS and the Residential Energy Consumption Survey, or RECS (Energy Information Administration (US), 2009a, 2009b). We found that more data points for developing a simple regression model would be available by interpreting CBECS and RECS data at the Census division level. We also found that the best curve fits for historical data came from interpreting air conditioning demand as a function of ambient temperature rather than number of cooling degree days, which are population-weighted. For these reasons, it was most appropriate to use area-weighted climatological data for average monthly temperatures from the National Climatic Data Center, rather than population-weighted cooling-degree-day data. In order to use CMIP3 projections with regression models developed from demand data from EIA, monthly temperature changes from the CMIP3 models were area-weighted in accordance with methods used by the National Climatic Data Center (National Oceanic and Atmospheric Administration (US), 2009) for average monthly temperatures. It should be noted that regression models developed from EIA data endogenize mechanisms for increased use of air conditioning at higher temperatures, such as increased market penetration. Results for temperature change projections are summarized in Table 2.

Under projections for serious climate change by 2050 (A2 scenarios), about 770 TWh of electricity would be used for increased air conditioning. Under projections for mild changes in climate (B1 scenarios), only about 67 TWh would be used.

Table 2
Division-level projections for average summer temperature (degrees Celsius) in the continental US by 2050 utilized for this analysis. Source data from WCRP CMIP3 and the National Climatic Data Center (World Climate Research Programme Coupled Model Intercomparison Project phase 3 (WCRP CMIP3), 2010; National Oceanic and Atmospheric Administration (US), 2008).

Division	Normal	B1	A2	Area weight	Region	Normal	B1	A2
New England	18.4	17.9	20.8	0.39331	Northeast	19.3	19.1	21.9
Mid Atlantic	19.9	19.9	22.7	0.60669				
E N Central	20.9	21.3	24.7	0.32433	Midwest	21.5	21.8	25.5
W N Central	21.8	22.0	25.9	0.67567				
S Atlantic	24.9	25.3	27.7	0.30992	South	25.9	26.4	29.8
E S Central	25.1	26.1	29.6	0.20225				
W S Central	26.9	27.4	31.2	0.48782				
Mountain	20.1	20.9	24.2	0.72732	West	20.2	20.2	23.3
Pacific	20.3	18.3	21.1	0.27268				

[1] For readers familiar with recent literature on PHEVs, our focus on longer-range batteries may raise questions. However, our assumptions are consistent with findings of one of the most detailed studies to date on tradeoffs associated with batteries of different electric ranges Shiau et al., 2009. The assumptions for our upper-bound world would most closely resemble a future that prioritizes greenhouse gas reductions (hence PHEVs rather than traditional hybrid vehicles would be the preferred technology). Additionally, our focus on longer-range batteries assumes that consumers will opt to purchase vehicles that minimize fossil fuel consumption. This may be a preferred technology should gasoline prices by 2050 be especially high, such as in the neighborhood of $6.00 per gallon.

[2] Although the SRES features six scenario families, it should be noted that the Working Group I contribution to the IPCC Fourth Assessment Report (Meehl et al., 2007) also focuses primarily on the A1B, A2, and B1 scenario families.

Table 3
State-level projections for new electricity demands in 2050 due to desalinating public water supplies in the Western U.S. and Florida. Source data from the U.S. Census Bureau, the U.S. Geological Survey, and the U.S. National Research Council (US Census Bureau, 2005; National Research Council (US), 2008; US Geological Survey, 2009).

	Census 2000 (millions)	Census projection 2030 (millions)	Projection[a] 2050 (millions)	Projected consumption[a] 2050 (Bgal/day)	Desalination electricity demand[b] (BkWh)
Arizona	5,130,632	10,712,397	17,451,082	3.9	27.22
California	33,871,648	46,444,861	57,298,006	11	76.61
Colorado	4,301,261	5,792,357	7,018,428	1.7	11.68
Florida	15,982,378	28,685,769	42,368,330	7.3	50.15
Nevada	1,998,257	4,282,102	7,088,290	2.3	15.96
New Mexico	1,819,046	2,099,708	2,176,250	0.4	2.97
Utah	2,233,169	3,485,367	4,676,610	1.3	8.98
Total	65,336,391	101,502,561	138,076,996	28	193.57

[a] Projected values are based on curve fits for source data provided by the U.S. Census Bureau and U.S. Geological Survey.
[b] This column reflects demand for delivered electricity. In the bounding analysis, such estimates were corrected by a factor of 9% to account for energy losses due to transmission.

2.3.3. Widespread use of heat pumps

Efficiencies for top-of-the-line central air conditioners and air-source heat pumps are comparable, so decreases in electricity demand due to the widespread use of heat pumps for cooling are expected to be negligible. However, the widespread substitution of heat pumps for space and water heating could add significantly to electricity demand.

The US National Renewable Energy Laboratory reports that the entire country is suitable for the use of ground-source heat pumps (Green and Nix, 2006). An Electric Power Research Institute (EPRI) report on expanding the end-uses of electricity to mitigate CO_2 emissions found that net emissions reductions could be achieved by a nationwide switch to heat pumps from fossil-fueled space, water, and industrial process heating (Electric Power Research Institute, 2009b). For the widespread use of heat pumps through 2030, EPRI considered two cases. One case demonstrated the "technical potential" of a 100% phase-in of top-of-the-line ground-source heat pumps (COP = 5.3) nationwide for space heating in residences and commercial buildings among other assumptions. However, the ground is not an unlimited heat source, and widespread use of ground-source heat pumps in densely populated areas could lead to precipitous drops in heat pump efficiency. Thus the 100% substitution of high efficiency ground-source heat pumps regardless of location was deemed too optimistic. Instead we used EPRI's case for "realistic potential" in which displacement of relevant fossil-fueled technologies by heat pumps through 2030 was capped at 50%.

Using EPRI's cumulative estimates across sectors and end-uses, five-year[3] increases in delivered electricity demand were estimated. These were then averaged to estimate annual increases in delivered electricity and used to approximate a time series of new electricity demand in each sector by end-use. Since the lifetimes of fossil-fueled technologies to be substituted range from 15 to 26 years, EPRI's projections through 2030 still leave much of the fossil-fueled technology stock to be turned over through 2050. For the upper bound, we estimated a substitution trajectory for heat pumps that matched EPRI's "realistic potential" case, where 50% of relevant fossil-fueled technologies were displaced by 2030. Extending this trajectory through 2050, widespread substitution of heat pumps for space and water heating could introduce up to 550 TWh of new electricity demand.

2.3.4. Widespread use of desalination for urban water supply

The effects of anthropogenic climate change on the arid Western US (California, Nevada, Utah, Colorado, Arizona, and New Mexico) have already been documented (Barnett et al., 2008). Furthermore, many of these states have growing populations.[4] Florida is another populous US state with high water needs, and saltwater intrusion due to sea level rise under a changing climate might further increase the need for water. It should be noted that ever since national records were kept for US water consumption in 1950, most water has been used for agriculture (Hutson et al., 2004). Due to the structure of US Western water law, (Wilkinson, 1992) there is recent evidence that when water becomes scarce, those holding water rights for agricultural use find it more profitable to sell water for urban consumption. Nevertheless, for the upper bound analysis, we assume that if water supplies become constrained, desalination would be used to support public water supplies. Between increasing regional populations, drought, and potential saltwater intrusion, a scenario is considered for the upper bound analysis where 100% of public water supplies in the aforementioned states must be desalinated (see Table 3). We do not assume that any desalination is used for agriculture.

Future public water supplies were assumed to be a function of state population. Projections for the demand of desalinated water and requisite electricity requirements were based on two assumptions: growth in volume of public water supplies as a function of state population, and electricity intensity of desalination. Geographically distributed state population projections through 2030 (US Census Bureau, 2005) were used to derive growth curves for state population through 2050.

After using population projections to estimate the size of public water demand in 2050, the electricity requirement for desalinating this water was estimated. The electricity intensity of reverse osmosis (RO) for ocean water[5] was selected to estimate the upper bound because the range of electricity intensity in the published literature for this particular technology includes the range of competing technologies (National Research Council (US), 2008). By 2050, if 100% of public water supplies in the southwestern states and Florida require desalination of ocean or similarly brackish waters, this would result in about 210 TWh of electricity demand.

2.3.5. Expanded use of electricity for process heating

The EPRI report (Electric Power Research Institute, 2009b) discussed above in Section 2.3.3 also assessed opportunities to substitute electricity-based technologies for some industrial process heating now performed with fossil fuels. The technical potential case reflects electricity technology phase-in at various market shares though 2030. Using the same approach discussed previously in Section 2.3.3 for heat pumps, EPRI's cumulative estimates for increased electricity demand across end-uses from 2010 to 2030 were extended to obtain an estimate of new electricity demand in 2050 of about 110 TWh.

[3] The EPRI study period was 2009–2030. Thus the cumulative gains for the year 2010 represent a two-year gain rather than a five-year gain, and the average annual increase for the period 2009–2010 is a two-year average rather than a five-year average.

[4] All Western states listed are party to the Colorado River Compact. The Compact has been criticized as an unrealistic agreement for the allocation of water between these states and Wyoming because updated streamflow reconstructions have found that initial allocations were negotiated during anomalous wet years Woodhouse et al., 2006.

[5] Reverse osmosis can also be used to desalinate brackish water, which is not as salty as ocean water and requires substantially less electricity to desalinate. However, because this analysis is considering the upper bound for electricity demand, only water with the salinity of ocean water is considered.

2.3.6. Electricity savings from aggressive efforts in energy efficiency

EPRI distinguished multiple tiers of electric energy efficiency potential (Electric Power Research Institute, 2009a). The types of potential that are relevant for this bounding analysis are “realistically achievable potential” (P_{RA}), or energy savings that are deemed most likely to occur, and “technical potential” (P_T), or energy savings that are technically possible. This distinction matters because E_{BASE_LO} is defined by a term that endogenizes electric energy efficiency improvement (e_{BASE_LO}). To ensure that the lower-bound estimate does not result in an underestimate, expected efficiency improvements endogenized in e_{BASE_LO} must be separated from additional electric energy savings that are technically possible but cannot be expected to occur without additional policy or program intervention.

For this analysis, P_{RA} was estimated by comparing e_{BASE_LO} to the baseline electricity intensity of two major energy efficiency studies — the EPRI study and a National Academies study (Electric Power Research Institute, 2009a; National Academy of Sciences (US)-National Academy of Engineering (US)-National Research Council (US), 2010). Both of these studies compare their results to baselines resembling the reference case of the 2008 *Annual Energy Outlook* (AEO) (Energy Information Administration (US), 2008). For this reason, e_{BASE_LO} was compared to the electricity intensity improvement of the AEO 2008 reference case, which is approximately −4.3 Wh/$GDP per year. Over the time period that defines the estimate for e_{BASE_LO} (1991–2007), electric energy intensity was approximately −4.5 Wh/$GDP per year. From these two rates for annual decreases in electricity intensity, the projected electricity intensity of the U.S. economy in 2050 could be found. By 2050, the electricity intensities are virtually identical, so P_{RA} in 2050 was projected to be approximately 1%.

Since P_{RA} was verified to be consistent with recent literature, P_T was estimated by literature review. A recent energy efficiency study completed by the National Academies found general agreement among eight studies of electricity efficiency in the built environment (National Academy of Sciences (US)-National Academy of Engineering (US)-National Research Council (US), 2010). As discussed in Section 2.1, our baseline electricity demand projection already endogenizes structural shifts in the US economy toward services. This suggests that by 2050, our baseline represents electricity use primarily in residential and commercial buildings. Across the studies for electricity savings in residential and commercial buildings, median technical potential was 33% of baseline demand for buildings, and median economic potential was 24%. Since residential and commercial demand represent 78% of total delivered electricity by 2030 in the AEO 2008 reference case, the National Academies results translate to electricity savings of 25% of total consumption (where losses due to transmission are taken into account).

EPRI arrived at more conservative conclusions for economic potential — only 14% by 2030 (Electric Power Research Institute, 2009a). However, EPRI's estimate for technical potential was 29% of total electricity consumption by 2030, which is in the neighborhood of the aforementioned studies. EPRI also presented estimates for efficiency potentials at a number of future times. Using the time-based estimates from the EPRI study, this bounding analysis approximates a logarithmic growth function for electricity savings from aggressive efficiency improvements through 2050 — culminating in savings that are approximately 34% of total electricity consumption.

3. Results

Summing the various estimates discussed above we construct an upper and lower bound on US electricity demand in the year 2050 as shown in Fig. 4.

The upper bound is the sum of the upper baseline case and the high estimates for all new electricity demands greater than zero. It represents a future where serious climate impacts, such as much higher summer temperatures and sustained water stress, become significant by 2050.

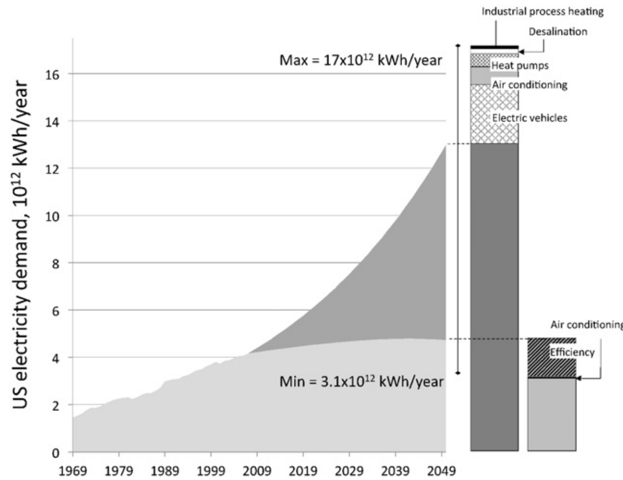

Fig. 4. Bounding analysis of US electricity demand in 2050. The upper case assumes sustained GDP growth of about 3.3% per year with modest electricity intensity improvement (−2.5 Wh/$GDP/year). Longer-range (60-km, or 40-mile range) batteries were assumed for plug-in hybrid electric vehicles. The lower case assumes GDP growth of 1.8% per year with sustained electricity intensity improvement (−4.5 Wh/$GDP/year).

In this case, mitigation strategies that decrease net US CO_2 emissions, but increase electricity demand, are also realized such as electrification of some industrial process heating (plasma melting, electrolytic reduction, electric induction melting, electric arc furnace), high penetration of efficient heat pumps (phase-in potential of 50%, substituting for gas, oil, and other fossil fuels), and high penetration of longer-distance PHEVs (100% of LDV fleet). However, it is also assumed in creating this bound that accelerating electric energy efficiency has not become a high priority, which would result in negligible changes to baseline US electricity intensity. The sum of new electricity demands (E_{NEW_HI}) represents about 4100 TWh of additional demand, which is approximately 32% of the upper baseline. Conversion of the LDV fleet to longer-range (60 km, or 40 mile) PHEVs introduces the largest share of increased demand (19% of the baseline). Increased use of air conditioning represents an additional 6%, wide deployment of heat pumps represents another 4%, desalination of public supplies for selected states adds 2%, and electricity substitutions for some industrial process heating adds 1%. Grouped by category, new electricity demands that would be the result of adaptation to impacts from climate change (increased use of air conditioning, desalination) represent an additional 8% to nationwide electricity use, while demand that would be the result of mitigation strategy (expanding end-uses of electricity to substitute fossil fuel use in transport and heating) represent an additional 24%.

The lower bound for electricity demand in 2050 is the sum of the lower baseline case, a low estimate for new electricity demand due to air conditioning (based on minimum projected temperature change), and aggressive efficiency improvements as summarized previously in Table 1. The lower bound represents a future where climate impacts, such as higher summer temperatures and regional water stress, are mild by 2050. In fact, lower bound projections for summer temperature change from the WCRP database (World Climate Research Programme Coupled Model Intercomparison Project phase 3 (WCRP CMIP3), 2010) for the US are virtually indistinguishable from the 1971–2000 normal.

Electricity efficiency improvements are assumed to be a top priority in this scenario. Technologies widely deployed in the upper-bound case, such as electrification of some industrial process heating, heat pumps, and long-distance PHEVs, are not significantly deployed in the lower-bound case because noneconomic market barriers that currently prevent wide deployment (e.g. perceived hassle of adopting new technologies) were assumed to persist through 2050. Since the projected increase in average summer temperature is very small, increased use of air conditioning under this mild climate change represents only a

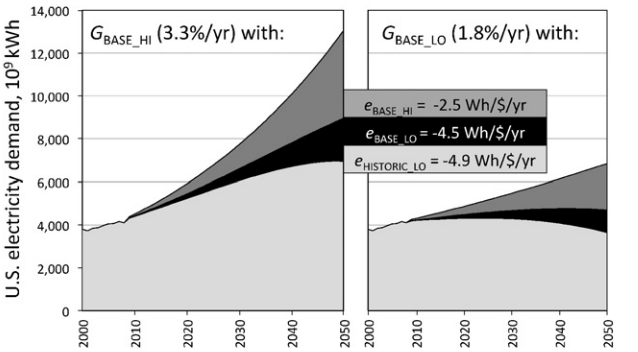

Fig. 5. Illustration of effect on US electricity demand profile with changes in assumptions for the rate of electricity intensity improvement.

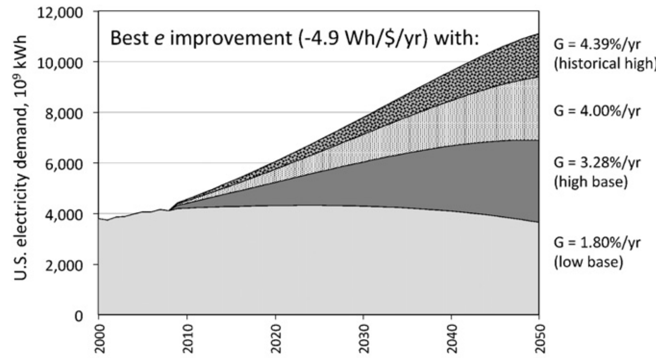

Fig. 6. Illustration of effect on US electricity demand profile with changes in assumptions for the rate of GDP growth.

1% increase to baseline demand. The 34% electricity efficiency improvement is an estimate for what additional electricity savings could be by 2050. The additional electricity improvement represents about 1600 TWh in savings, which drops projected electricity use down to approximately 3100 TWh from 4700 TWh.

4. Sensitivity analysis

Projections for baseline electricity demand of course depend on assumptions about GDP growth and electric energy intensity improvement. Changes in the baseline due to changes in the rate of electricity intensity improvement and GDP growth are discussed below.

4.1. Changes in electric energy intensity improvement

As discussed in Section 2.1, there are at least three long-term trends for the rate of change of e over the 1976–2007 period. As illustrated in Fig. 5, different assumptions for this rate of change can dramatically shift when and if US electricity demand may be expected to level off. When e is modest (<-3.0), demand shows no signs of leveling off by 2050 even when GDP growth is low.

4.2. Changes in GDP growth

Also discussed in Section 2.1 were annual rates for the growth of US GDP. Other rates for US GDP growth were determined by running a 40-year window across historical data and fitting exponential curves to the 40-year trends. Over the 1949–2007 period, US GDP growth was found to range from around 3.0% to 4.4% with lower values being more recent (i.e. US GDP growth has been slowing over time). Since it is possible that US GDP could enter another prolonged period of robust growth, all rates for GDP were investigated in the sensitivity analysis. Holding electric energy intensity (e) constant, changes in GDP growth shift only slightly the future time at which US electricity demand would be expected to start leveling. Fig. 6 demonstrates this finding with the best improvement for energy intensity historically observed, where $e = -4.9$ Wh/$GDP per year.

5. Discussion

The magnitude of the new electricity demand term (E_{NEW}) can be sufficiently large in either direction to be relevant for long-term energy projections. When the new term represents additional electricity needs (E_{NEW_HI}), it can be nearly 33% of upper baseline demand and nearly 90% for the lower baseline.[6] Among new electricity demands, the greatest contributor would be the widespread deployment of PHEVs. Grouped by category, new electricity demands that would be the result of adaptation to impacts from climate change represent an additional 8% to nationwide electricity use (an additional 21% for the lower baseline), while demand stemming from mitigation strategy represents an additional 24% (67% for the lower baseline). When the new electricity demand term represents electricity savings (E_{NEW_LO}), it could amount to a decrease of about 34% of total electricity consumption over a 40-year time horizon. From these results, it is clear that policy interventions that prioritize electricity efficiency do more than simply harvest low-hanging fruit; maximizing efficiency becomes necessary if one wants to significantly limit the future growth of US electricity demand over the coming decades.

Our projections for baseline electricity demand of course depend on assumptions about GDP growth and electric energy intensity improvement. Other scholars have similarly noted that assumptions for these parameters affect the accuracy of US energy consumption projections (O'Neill and Desai, 2005). From the sensitivity analysis, it is apparent that assumptions about the rate of change for electric energy intensity are most important, as it is the intensity improvement that levels electricity demand by 2050 in both the upper and lower baselines (c.f. Fig. 5).

5.1. Comparison of results to other electricity demand projections

Few electricity demand projections consider a time horizon as far out as 2050. The 2013 *Annual Energy Outlook* (AEO) includes projections to 2040, and compares its findings to projections produced by the National Renewable Energy Laboratory (NREL), IHS Global Insight, and Energy Ventures Analysis (EVA) (Energy Information Administration (US), 2013). The 2013 AEO features a comparison of these four projections, which are all based on modeling that is much more detailed than the bounding analysis of this paper. For 2040, the 2013 AEO reference case projects 5200 TWh of total electricity demand (total generation including CHP plus imports), while NREL projects 4900 TWh, IHS projects 6200 TWh, and EVA projects 5500 TWh. Our low baseline projection for the year 2040 is 4800 TWh, while our high baseline is 10,000 TWh. Thus the projections from these other models are near our low baseline.

AEO explains that its projections for the reference case reflect existing policies and exclude the influence of new policies, the anticipation of major technological breakthroughs, or other possibilities that might substantially deviate from recent or historical trends. In effect, the reference case is a detailed projection of current conditions into the far-off future. A more relevant comparison to the baseline cases of our analysis may be the AEO high and low economic growth cases, which by 2040 are 5500 TWh and 4600 TWh of electricity demand respectively. Our high and low baselines for 2040 are 10,000 TWh and 4800 TWh. Thus our low baseline is in close agreement with AEO, while our high baseline is twice as high as the high AEO case. As discussed above in Section 5, this major difference is likely due to our

[6] The lower baseline estimate reflects the same future described in Section 2.3 but with slower economic growth characteristic of the lower baseline (1.8% per year).

interpretation of much slower improvements in electricity intensity in the high baseline, although our high economic growth assumption (3.3% real growth) is also higher than AEO (2.9% real growth for the high economic growth case).

5.2. Other potential developments not considered

As discussed in Section 2.1, many historical trends are endogenized in the baseline projection. This includes current trends for major uses of electricity as well as the distribution of the US population. Should natural gas prices in the US stabilize at low levels, it is conceivable that massive fuel switching from electricity to natural gas might occur for end uses such as cooking and clothes drying (Costello, 2009). Potentially, this could result in a lower bound estimate for electricity demand that is below what is discussed in this paper.

With respect to population, this analysis has not considered the possibility of major changes in the spatial distribution and rate of change of population patterns in the US. Cities in states with some of the most rapid population growth (Phoenix, Arizona; Las Vegas, Nevada; Miami, Florida; Atlanta, Georgia) were hardest hit by the implosion of the US housing market. In April of 2009, the Census Bureau reported that mobility had been substantially affected by the recession (Roberts, 2009). Slow economic recovery could potentially dampen migration and population growth for US states in the "Sun Belt," which includes California, southern Nevada (Las Vegas), Arizona, Texas, Florida, and Georgia. However, in a discussion of the relationship between long-term population trends and housing supply, economist Edward Glaeser noted that despite overbuilding in portions of the Sun. Belt, the collapse of the housing market should be viewed as a correction, and population growth in the southern US is likely to resume (Glaeser, 2010). Should population growth in the south decrease, it would likely decrease electricity demand for cooling.

While our analysis has included a range of new technologies, we have *not* included dramatic technological changes such as autonomous vehicles, dramatically less costly and higher density energy storage, electric aircraft, the development of low cost direct air capture of CO_2, or similar radical innovations. While many such developments are possible, we believe it is unlikely that they would see wide adopted before 2050.

6. Conclusion

This paper demonstrates how bounding analysis can be used to address overconfidence in long-term energy demand projections. Using US electricity demand in 2050 as a case study, bounding analysis has been used to explore consequences of sustained trends, expansion of the end-uses of electricity, and adaptation to impacts of serious climate change. Bounding analysis integrated with traditional systems models, perhaps through probabilistic model switching as discussed by Casman et al. (1999) could better limit overconfidence for projections over long time frames than detailed systems models alone. A parsimonious modeling approach like that demonstrated here could be particularly useful for investigating policy relevant but uncertain (or even unanticipated) scenarios over the long term. For today's policymakers, long-term projections that are informed by simple bounding analyses may more usefully quantify the benefits of near-term mitigation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2015.09.001.

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