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 3,100 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.

Keywords: long-term electricity demand projections; climate change; bounding analysis

1 Introduction

Past efforts to project future US electricity or overall energy consumption 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). Yet analysts intent on examining a range of issues, including the implications of future climate change, need plausible projections as inputs to their work.

The Intergovernmental Panel on Climate Change (IPCC) addressed this issue in its Third and Fourth Assessment Reports by developing a range of scenarios based on detailed story lines (Nakicenovic et al., 2000). 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 or used (Schweizer and Kriegler, 2012). For the next round of IPCC assessment, a new approach decoupling general emissions trajectories from detailed storylines has been developed (Moss et al., 2010; O'Neill and Schweizer, 2011). Nevertheless, there are plans to couple general emissions trajectories with detailed story lines (Arnell et al., 2011).

Morgan and Keith (2008) have provided a detailed critique of such scenario methods, arguing 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" (Dawes, 1988). They and Casman et al (1999) suggest that when uncertainty is high, simple bounding analysis may offer a more promising analytical strategy. In this paper, we perform such an analysis to bound the plausible range of US electricity demand in the year 2050.

2 Method

We begin by decomposing the problem using the simple identity:

$$E = G \times \left(\frac{E}{G}\right) = Ge \tag{1}$$

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 equation (1) as a subset of the larger identity used to characterize energy-related greenhouse gas emissions. It should be noted that equation (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 $G_{\mathrm{BASE\_LO}}(t)$ and $G_{\mathrm{BASE\_HI}}(t)$ and then construct:

$$E_{\mathrm{LO}}(t) = E_{\mathrm{BASE\_LO}}(t) + E_{\mathrm{NEW\_LO}}(t) = \left(G_{\mathrm{BASE\_LO}}(t)\right)\left(e_{\mathrm{BASE\_LO}}(t)\right) + E_{\mathrm{NEW\_LO}}(t) \tag{2}$$

$$E_{\mathrm{HI}}(t) = E_{\mathrm{BASE\_HI}}(t) + E_{\mathrm{NEW\_HI}}(t) = \left(G_{\mathrm{BASE\_HI}}(t)\right)\left(e_{\mathrm{BASE\_HI}}(t)\right) + E_{\mathrm{NEW\_HI}}(t) \tag{3}$$

which we evaluate in the year 2050. In this case, $E_{\mathrm{NEW\_LO}}(t = 2050)$ 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, $E_{\mathrm{BASE\_LO}}(t = 2050)$. Similarly $E_{\mathrm{NEW\_HI}}(t = 2050)$ 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, $E_{\mathrm{BASE\_HI}}(t = 2050)$.

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 (BEA, 2008) reveal that from 1949-2007, 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 Figure 1. The *Annual Energy Outlook* (EIA 2008), a series of energy demand projections published each year by the US Energy Information Administration, considers 25-year trends of average US GDP growth as low as 1.8% in its low economic growth case.

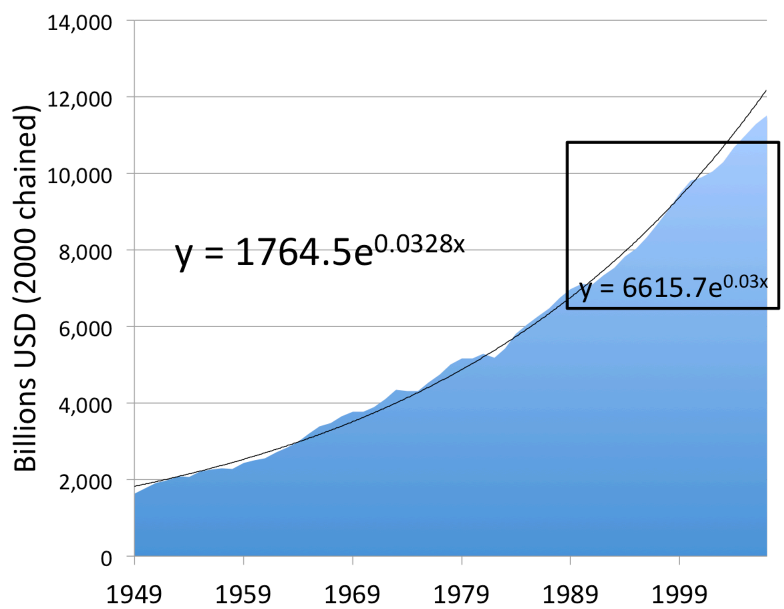

Figure 1. Two possible curve fits for long-term growth in US GDP. The main curve over the 1949-2007 period yields an annual growth rate of about 3.3%. Over the 1990-2007 period (boxed), US GDP growth is more modest at 3%. Source data from BEA (2008).

We used these different values of 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 equation (1)) by examining the historical trend of the ratio of electricity generated to GDP, which is shown in Figure 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 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.

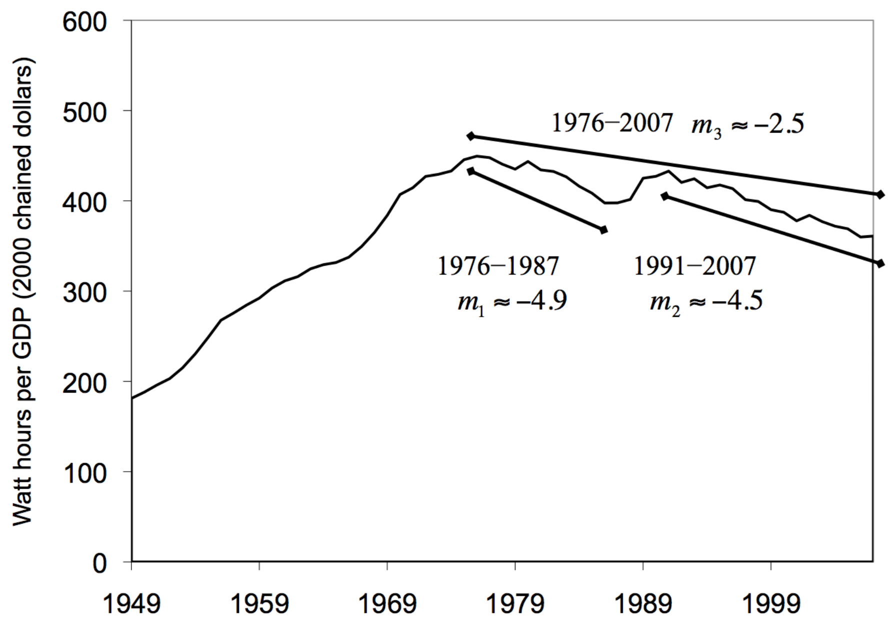

Figure 2. Mid-term trends in decreasing aggregate electricity intensity for the US economy over three periods, 1976-1987, 1991-2007, and 1976-2007.
Source data from EIA (2009) and BEA (2008).

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 $E_{\text{BASE\_LO}}(t)$, *e* continues to decrease at 4.5 Wh/$GDP each year, while the economy grows at 1.8%. In $E_{\text{BASE\_HI}}(t)$, *e* continues to decrease at 2.5 Wh/$GDP, and the economy grows at 3.3%. By 2050 $E_{\text{BASE\_HI}}(t)$ has grown to nearly 13,000 TWh of total electricity demand by 2050, while $E_{\text{BASE\_LO}}(t)$ 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.

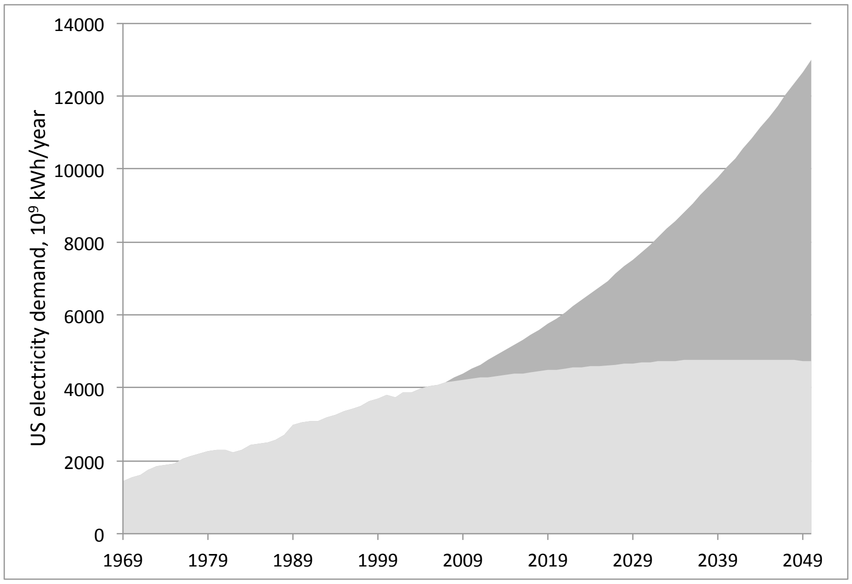

Figure 3. The upper- and lower-case baselines for US electricity demand in 2050 obtained by combining high and low projections of GDP growth with high and low projections of the electricity intensity of the US economy. Electricity demand for the upper baseline approaches 12,000 TWh in 2050, while the lower baseline falls to just under 4000 TWh.

2.2 Possible technical and behavioral developments

By 2050, the high and low baselines sketched in Figure 3 might be further affected by a range of technical and behavioral developments. In discussion with colleagues, we developed and refined a list of such possible developments. 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 (EPRI, 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.

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

	Increases electricity demand	Decreases electricity demand
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 o Energy-efficient shells and lighting for new construction o Energy-efficient shells and lighting for renovations o Performance standards for office and HVAC equipment

[a] Although machine drives currently comprise the bulk of industrial sector electricity demand, EPRI estimates that the realistically achievable potential of efficiency improvements will approach the economic potential by 2030. See EPRI (2009a) *Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the US (2010-2030)* 1016987. Palo Alto, CA. Since realistically achievable efficiency improvements are already endogenized in the bounding analysis, it would be redundant to estimate them separately.

2.3 Estimating new US electricity demands and savings in 2050

Here 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. Additional details on how these quantities were estimated are provided in Electronic Annexes as noted below.

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. 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 (BTS, 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. Readers interested in the details of this estimate should consult Electronic Annex 1 in the online version of this article.

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; readers interested in further details should consult Electronic Annex 1 in the online version of this article.

Projections for summer temperature change in the US by 2050 were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (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 4-5 W/m^2, which is about half of the radiative forcing of A2 (Meehl et al., 2007). 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).

In order to use them with 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, or NCDC (2009), for average monthly temperatures. Results for temperature change projections are summarized in **Table 2**.

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 (2010) and NCDC (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	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				

Simple projections of electricity demand due to increased use of air conditioning were a function of area-weighted average summer temperatures at the Census region level and were based upon historical data. Historic data were obtained from periodic estimates for commercial building and residential air conditioning at the level of Census divisions from the EIA Commercial Building Energy Consumption Survey, or CBECS (EIA, n.d.-a) and the Residential Energy Consumption Survey, or RECS (EIA, n.d.-b).

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.

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 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 (EPRI, 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 15-26 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 that by 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. 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 (NRC, 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 (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, which are summarized in Electronic Annex 1 in the online version of this article. 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 2010-2030 were extended to obtain an estimate of new electricity demand in 2050 of about 110 TWh.

2.3.6 Electricity savings from aggressive efforts in energy efficiency

EPRI (2009a) distinguishes multiple tiers of electric energy efficiency potential. 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_{BAU} is defined by a term that endogenizes electric energy efficiency improvement ($e_{\mathrm{BASE\_LO}}$). To ensure that the lower-bound estimate does not result in an underestimate, expected efficiency improvements endogenized in $e_{\mathrm{BASE\_LO}}$ 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 $e_{\mathrm{BASE\_LO}}$ to the baseline electricity intensity of two major energy efficiency studies – the EPRI (2009a) study and a National Academies study (NAS-NAE-NRC, 2010). Both of these studies compare their results to baselines resembling the AEO 2008 reference case, so $e_{\mathrm{BASE\_LO}}$ 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 $e_{\mathrm{BASE\_LO}}$ (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%. Readers interested in the details of this verification should consult Electronic Annexes 1 and 2.

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 (NAS-NAE-NRC, 2010). 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 load.

EPRI (2009a) arrived at more conservative conclusions for economic potential – only 14% by 2030. However, EPRI's estimate for technical potential was 29% of total load 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 load.

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 **Figure 4**.

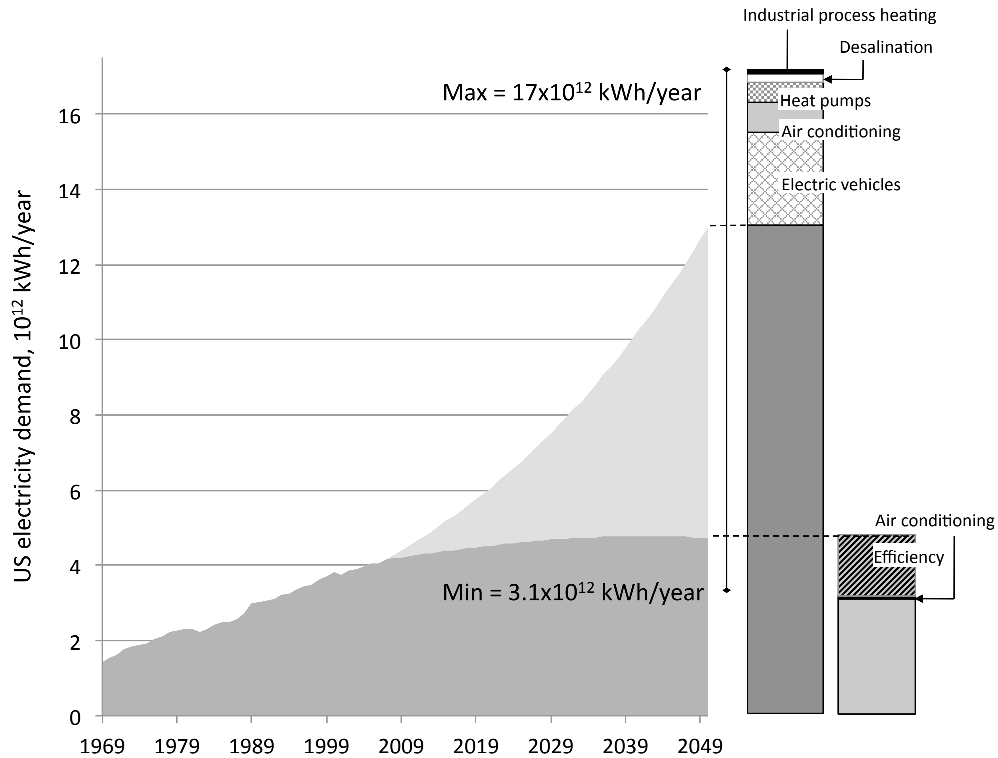

Figure 4. Bounding analysis of US electricity demand in 2050. The upper case assumes sustained GDP growth of about 3.3% per year with modest electricity intensity improvement (-2.5 Wh/\$GDP/year). Longer-range (60-km, or 40-mile range) batteries were assumed for plug-in hybrid electric vehicles. The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

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. 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 ($E_{\mathrm{NEW\_HI}}$) 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 (2010) database for the US are virtually indistinguishable from the 1971-2000 normal.

Electric 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 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 Figure 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.

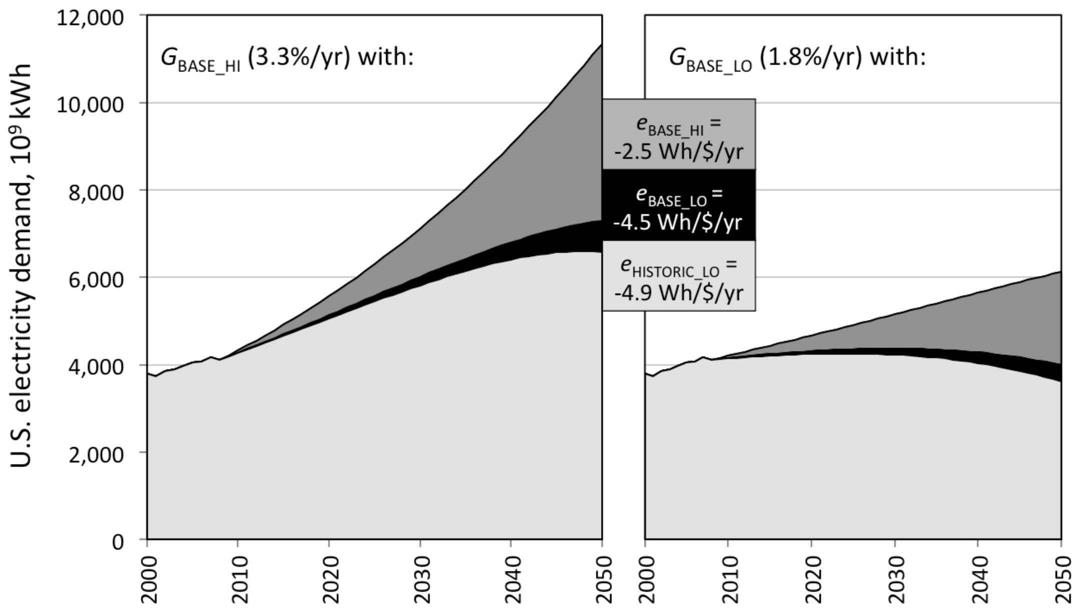

Figure 5. Illustration of effect on US electricity demand profile with changes in assumptions for the rate of electricity intensity improvement.

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. **Figure 6** demonstrates this finding with the best improvement for energy intensity historically observed, where e = -4.9 Wh/$GDP per year.

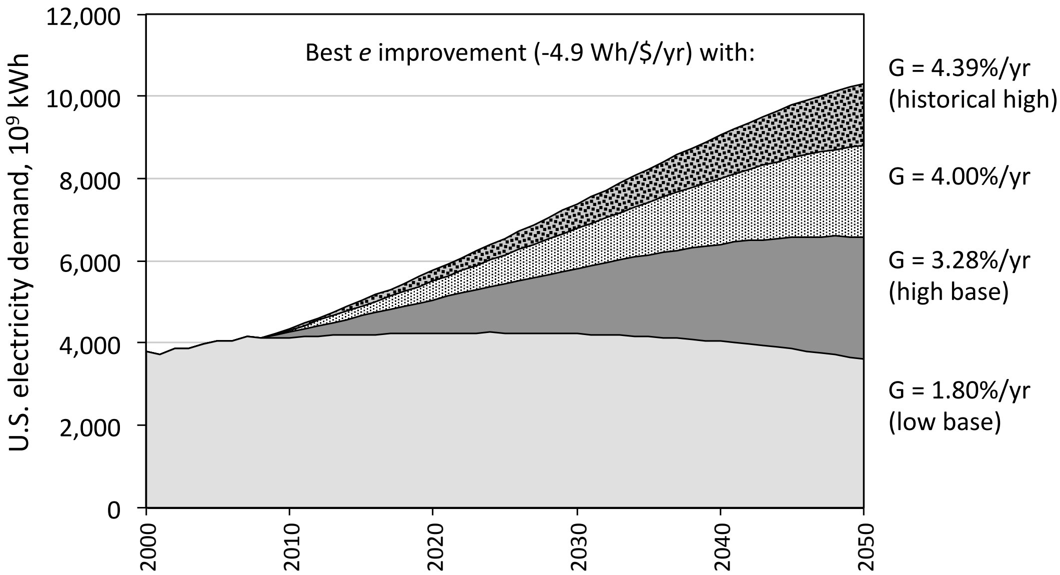

Figure 6. Illustration of effect on US electricity demand profile with changes in assumptions for the rate of GDP growth.

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 load 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 the upper and lower baselines (c.f. Figure 5).

5.1 Major population shifts

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.

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 scenarios that are extended by simple bounding analyses may more usefully quantify the benefits of near-term mitigation.

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8 References

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9 Footnotes

[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 the most detailed study 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 also focuses primarily on the A1B, A2, and B1 scenario families. See Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J. & Zhao, Z.-C. (2007) Global Climate Projections. IN Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L. (Eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* New York, Cambridge University Press.

[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. See Woodhouse, C. A., Gray, S. T. & Meko, D. M. (2006) Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research,* 42, W05415, doi:10.1029/2005WR004455**,** 16 pp.

[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.

[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).