Future U.S. Energy Use for 2000-2025 as Computed with Temperatures from a Global Climate Prediction Model and Energy Demand Model

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1. Introduction

The increase in atmospheric CO_2 that has been observed continues and will result in changes in atmospheric temperatures. The National Assessment Synthesis Team identified in *Climate Change Impacts on the United* States (NAST 2000) many processes that will be affected by climate change. One little-studied aspect of warming will be a climate-related change in the amount of heating and cooling needed by buildings in the U.S. These changes will increase or decrease the cost to consumers, depending on the types of energy used. The changes will affect the various regions of the country differently, with some possibly seeing a higher cost and others a lower cost. Overall carbon emissions could also change, leading to a slight feedback effect on climate change.

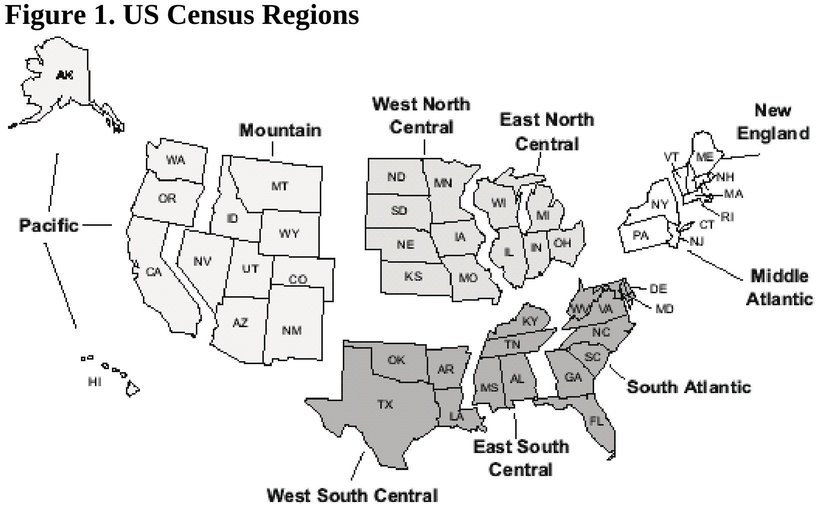
To calculate the change in energy demand, carbon emissions, and associated financial impacts of alterations in heating and cooling, three elements are needed: regional data on temperatures past and future, conversion of temperature changes into heating and cooling requirements, and a model to translate the requirements into energy use and economic consequences. Rosenthal, Gruenspecht, and Moran in 1995 used results from five global circulation models and national building survey data to estimate cost impacts (Rosenthal et al. 1995). We used data from the PCM-IBIS climate simulator, National Climatic Data Center (NCDC) information on heating and cooling degree-days, and a modified version of the National Energy Modeling System (NEMS) called DD-NEMS for these three elements.

This paper presents the results through 2025 from one PCM-IBIS scenario and the reference assumptions from the *Annual Energy Outlook 2003* (EIA 2003a). While of limited scope and time frame, it provides insight into the national and regional impact on energy use and costs from changing temperatures over time.

2. Methodology

The PCM-IBIS model provides surface temperature data on 2.5° x 2.5° latitude-longitude increments across the globe for every 15 minutes from 1900 to 2100 (Thompson et al., 2004). It uses a version of the Parallel Climate Model (PCM) (Barnet et al., 2002; Meehl et al.; 2000; Washington et al., 2000). The data for the U.S. was aggregated both geographically and temporally into the monthly average temperatures for each of the nine census regions (Figure 1) for 1971 to 2025. For this analysis only one PCM-IBIS computer run was used. Further analysis should be done using an ensemble of cases to establish more robust results.

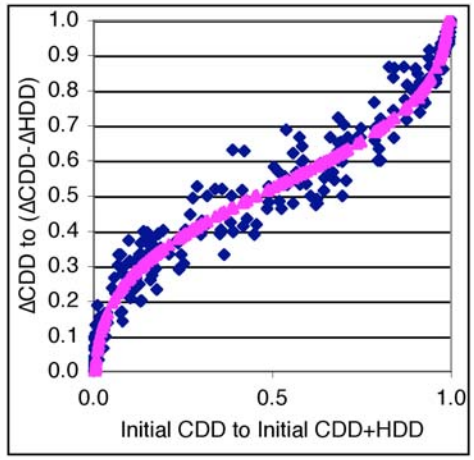
Figure 1. US Census Regions



The main metrics of the effect of outside temperature on heating or cooling loads are heating degree-days (HDD) and cooling degree-days (CDD). These measure the difference between the average ambient temperature for the day and a given reference temperature, typically 65ºF. These values have been recorded for many years at numerous sites around the country. The NCDC publishes monthly degree-day values for cities, states, and regions (NCDC 2003a and 2003b). The regional values are weighted on the basis of population within the region to better represent the heating and cooling loads for buildings.

Since the PCM-IBIS data does not weight the temperature by population or convert the averages to degree-days, it was necessary to convert its monthly temperatures into degree-day values and calibrate them with the NCDC data. First, using a series of random-walk, simulated months we derived an algorithm for the cooling and heating degree-days as a function of the original CDD and HDD values and change in average monthly temperature from the original value (Figure 2). For example, a July with no HDD and an average temperature increase of 2ºF would have the CDD increase by 62, while a January with no CDD would see a reduction of the HDD by 62. Months with both HDD and CDD values would see a proportional change to each.

Figure 2. Change in CDD as function of initial CDD, HDD and temperature change



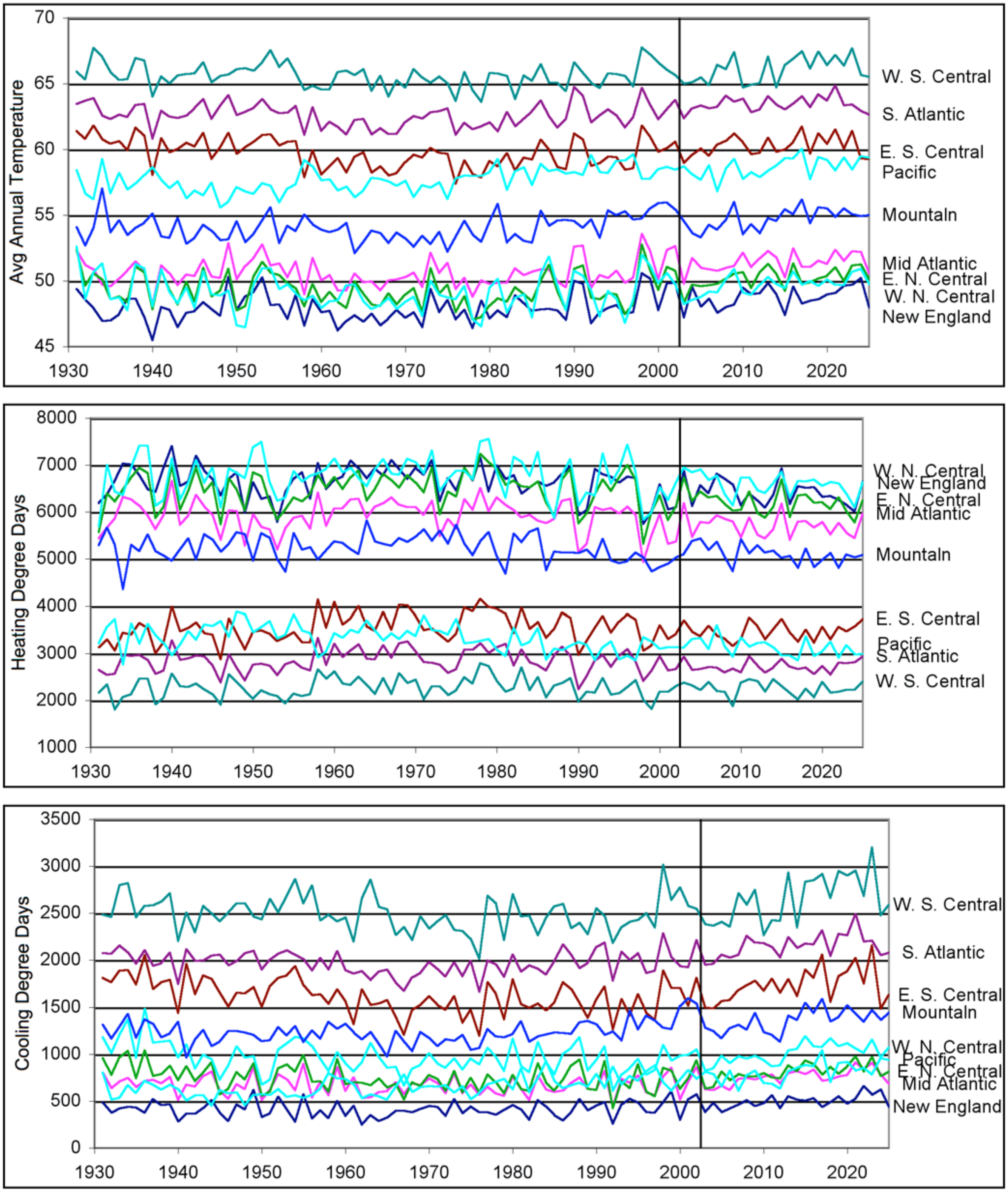
Once the algorithm was established, for each year 2003 to 2025 we calculated the PCM-IBIS monthly temperature change for each region as compared to the 1971-2000 average for the same region and month. Using those temperature changes and the average degree-day values for 1971-2000 from NCDC, we could calculate the degree-day amounts for future years (Figure 3). Note that both heating and cooling needs could increase in any year for a region if the data shows both hotter summers and cooler winters, or the opposite could occur with a flatter temperature profile.

Economic simulation involves modeling the economic decision-making of an energy-using sector or entire region. The stock of existing buildings and equipment, data on options available, decision procedures, energy prices, etc. need to be available for the model to attempt to realistically simulate the purchase behavior of people. The most widely recognized economic simulation model is the National Energy Modeling System (NEMS) (EIA 2003b). The EIA developed this model to forecast national and regional energy supply and demand through 2025. NEMS models the major end-use sectors of the economy: residential, commercial, industrial, and transportation. Within the energy sector, it models electricity, oil, gas, coal, and renewable energy production. It separates the nation into nine geographical regions for analysis (Figure 1), providing regional information on energy and economic results. This analysis used as a starting point the model and assumptions from the reference case of the *Annual Energy Outlook 2003* (EIA 2003a).

The standard NEMS model uses annual cooling and heating degree-day values for each region through the last year of available data and then uses the 1971-2000 average values for all subsequent years. We modified the model to accept annual temperature-related information through 2025. Accordingly, we call the model we used DD-NEMS to distinguish from the standard NEMS model. These temperature changes only directly affect the residential and commercial sectors. However, DD-NEMS can also calculate secondary impacts on other sectors such as electricity generation as the requirements alter energy supply needs. These effects will ripple through other sectors as energy supplies and prices change.

For this analysis, we ran two cases through DD-NEMS: the Base case with the post-2002 degree-days based on the NCDC 1971-2000 average, and a PCM case with degree-days varying by year according to the results from the PCM-IBIS run. DD-NEMS was run with eight full iterations, allowing supplies, demands, and prices to equilibrate.

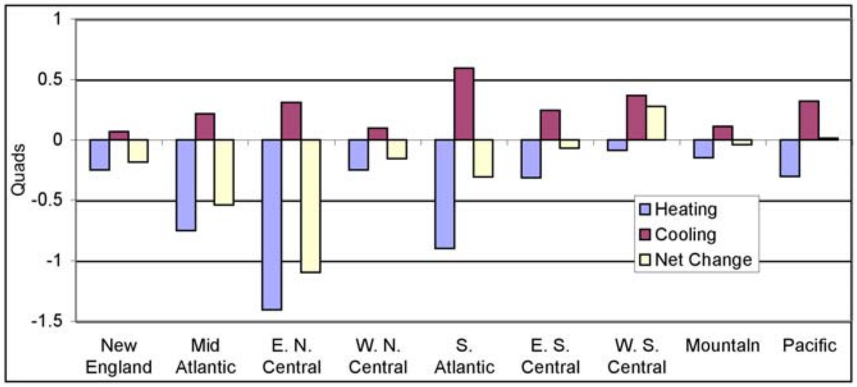
Figure 3. Annual average temperature, heating and cooling degree-day values from NCDC (pre-2002) and adjusted from PCM-IBIS (post 2002)



3. Energy Use Change

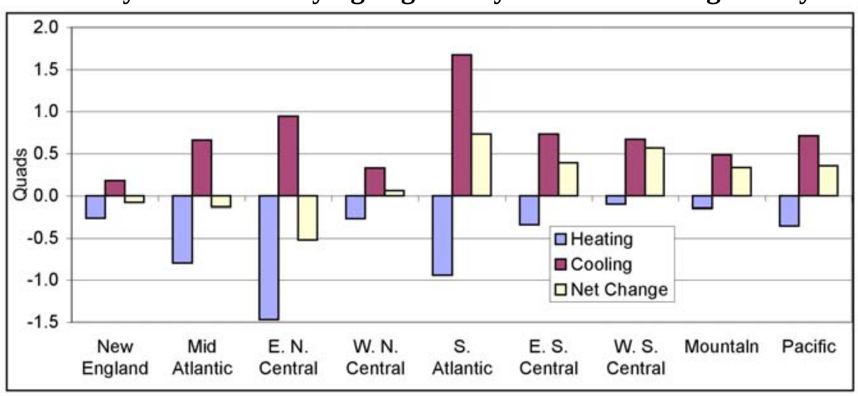
The most direct impact of temperature change on US energy use is the heating and cooling requirements for residential and commercial buildings. Each region will have different changes depending on the amount of heating and cooling needed as compared to the long-run average used in the base case. In general, the more northern regions of the country have a larger decrease in end-use heating needs than an increase in their cooling needs (Figure 4). The values shown are the sum of the change in end-use energy through 2025. The East-North Central region (mainly the Great Lakes states) has the largest overall decrease in energy, because of both its relative climate and large population. The West-South Central region shows a net increase in end-use energy as increased cooling requirements outweigh heating reductions.

Figure 4. Cumulative change in end-use heating and cooling energy between by 2025 with varying degree-days vs. constant degree-days.



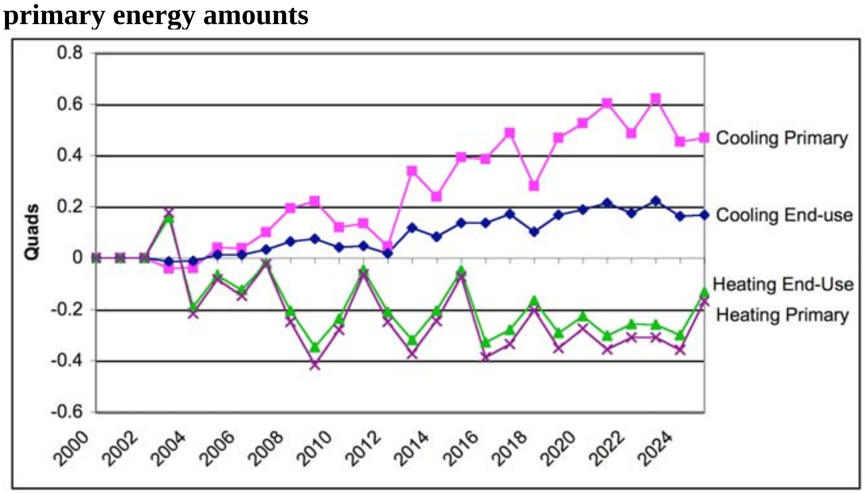
While end-use energy changes show the direct impact of temperature changes, the change in primary energy (which includes energy losses during electricity generation) is also important. Since electricity is used more for cooling than heating, the primary energy (the initial source of energy such as coal, oil, or gas) will change by a different amount than the end-use energy requirements. When adjustment for primary energy is added to each region, the net change in primary energy is positive for all but the northeastern regions (Figure 5). The southern regions (S. Atlantic, E. S. Central, and W. S. Central) have the largest change, likely due to the high penetration of air conditioning in these regions.

Figure 5. Cumulative change in primary heating and cooling energy between by 2025 with varying degree-days vs. constant degree-days.



Comparing the end-use and primary energy use over time (Figure 6), there is relatively little heating provided by electricity so there is little difference between end-use and primary energy. Cooling on the other hand is largely provided by electricity, with associated large losses during the manufacture of electricity from primary energy. The peaks and valleys in the curves reflect the changes in temperatures in the specific PCM-IBIS case used for this analysis. Increases in heating energy requirements in 2011 and 2015 reflect drops in temperatures for several of

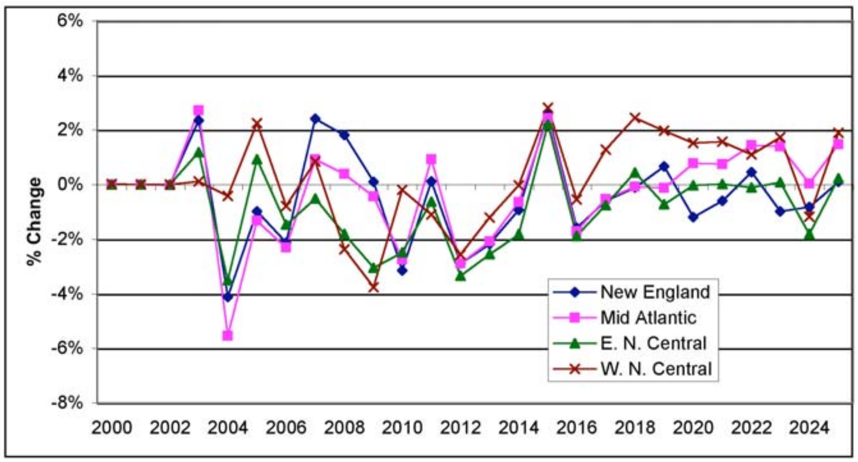
Figure 6. National change in heating and cooling end-use and primary energy amounts



the regions. The gradual increase in cooling requirements reflects the rise in cooling degree-days. In addition, DD-NEMS shows a small impact in follow-on years from degree-day changes in previous years. This may reflect the modeling of decision-making on equipment penetration or generating plant construction, or may be an artifact of the code not reflecting the volatility of changes solely for temperature swings.

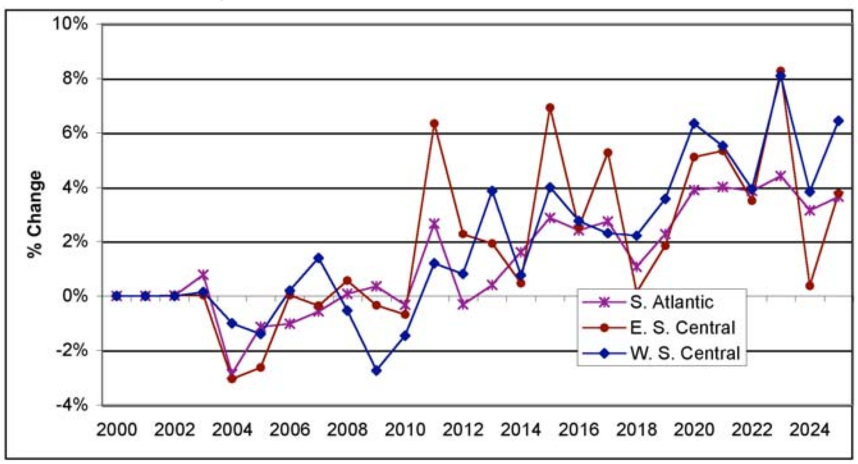
One interesting factor from Figure 6 is the early decline in heating needs that stabilizes around 0.3 Quads, while cooling needs continue to rise fairly consistently over the whole period. Those regions that most use space cooling will be most sensitive to the rise in cooling. Showing the change in primary energy for heating and cooling as a percentage of the primary energy used for heating and cooling in the base case reveals the relative impact of the energy change on the region's total energy use for this purpose.

Figure 7. Change in net primary energy use for heating and cooling in the northern and northeastern regions



The first four regions, in the northeast and central part of the U.S., show little change in energy use for most of the study period, with most fluctuations within 2% of the base amount (Figure 7). The Mid-Atlantic region (NJ, NY, PA) and W. N. Central region (IA, KS, MN, MO, NE, ND, SD) show a slight trend towards increasing net energy use over the study period. New England (CT, ME, MA, NH, RI, VT) and the E. N. Central states (IL, IN, MI, OH, WI) have lower and less variable energy needs. Air conditioning is not as widespread in these regions so cooling changes have less impact. Warmer winter's lower heating requirements outweigh the summer air conditioning needs.

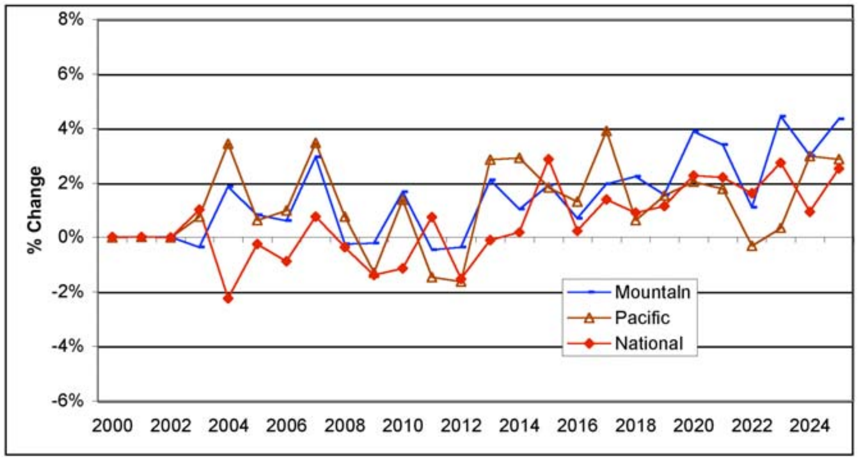
Figure 8. Change in net primary energy use for heating and cooling in the southern regions



In Figure 8, the three regions covering the southern states show a definite trend of increasing energy needs in the latter part of the study period, with net primary energy use increasing by as much as 8% in 2023. The W. S. Central region (AR, LA, OK, TX) is the region that has the largest net increase in end-use energy needs (Figure 4). The E. S. Central (AL, KY, MS, TN) has large early increases in energy needs. Over the whole period, the region has energy use increasing over 4%, with peaks over 8%. All values past 2010 are higher than if there were no change in degree-days over time. The S. Atlantic region (DE, DC, FL, GA, MD, NC, SC, VA, WV) shows a more steady increase over the period.

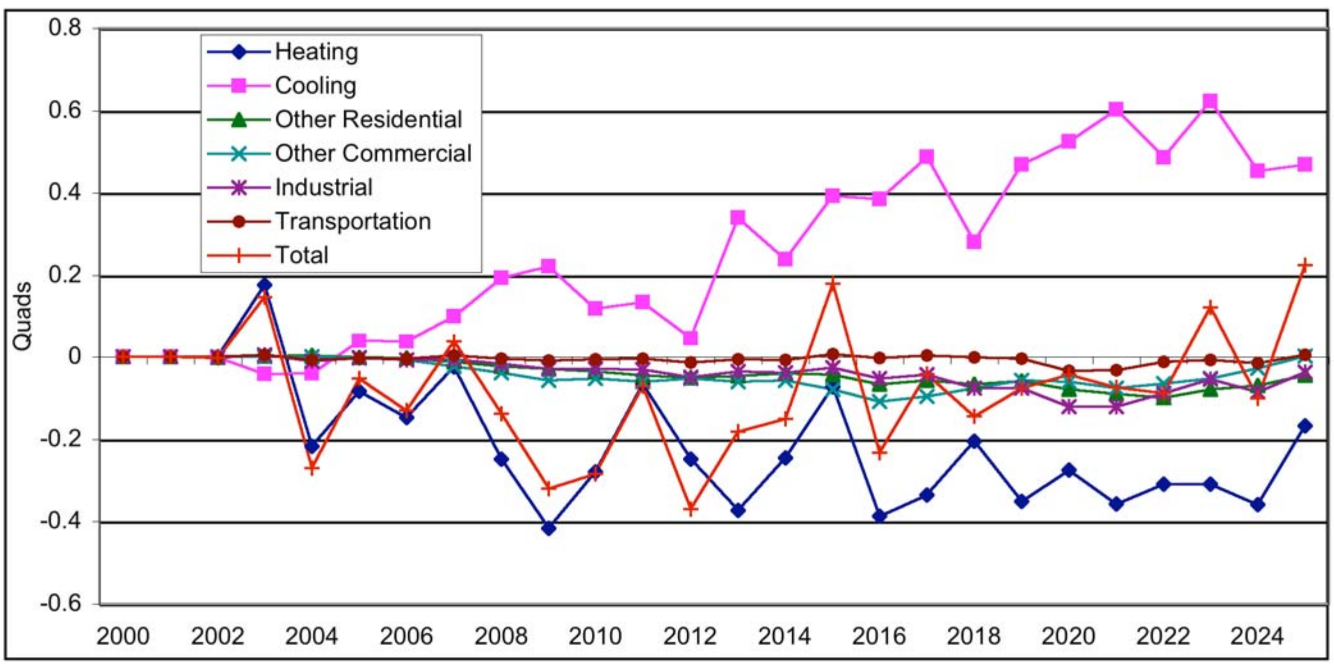
The last set of regional curves shows the western states and national average change (Figure 9). The Mountain region (AZ, CO, ID, MT, NV, NM, UT, WY) shows a steady increase over time, while the Pacific region (AK, CA, HI, OR, WA) is relatively consistent in the 0% to 4% range. Note that the temperature analysis from PCM-IBIS does not include Alaska because of large area compared to population. The National change is also shown, with energy use around 3% higher by the end of the study period.

Figure 9. Change in net primary energy use for heating and cooling in the western regions and Nationally



Because of the changes in energy use for heating and cooling, the supplies and prices for other energy uses will also change, which can in turn change the energy demands for non-heating and -cooling uses. These will generally be secondary to the change in heating and cooling, but since these latter two are opposite and so cancel each other out, the other uses become significant to the change in total energy use (Figure 10). Because DD-NEMS is a fully integrated model, the supplies and price changes flow to all sectors. Energy reductions in the other sectors, when combined, serve to moderate the net energy increase from space conditioning in the residential and commercial sectors.

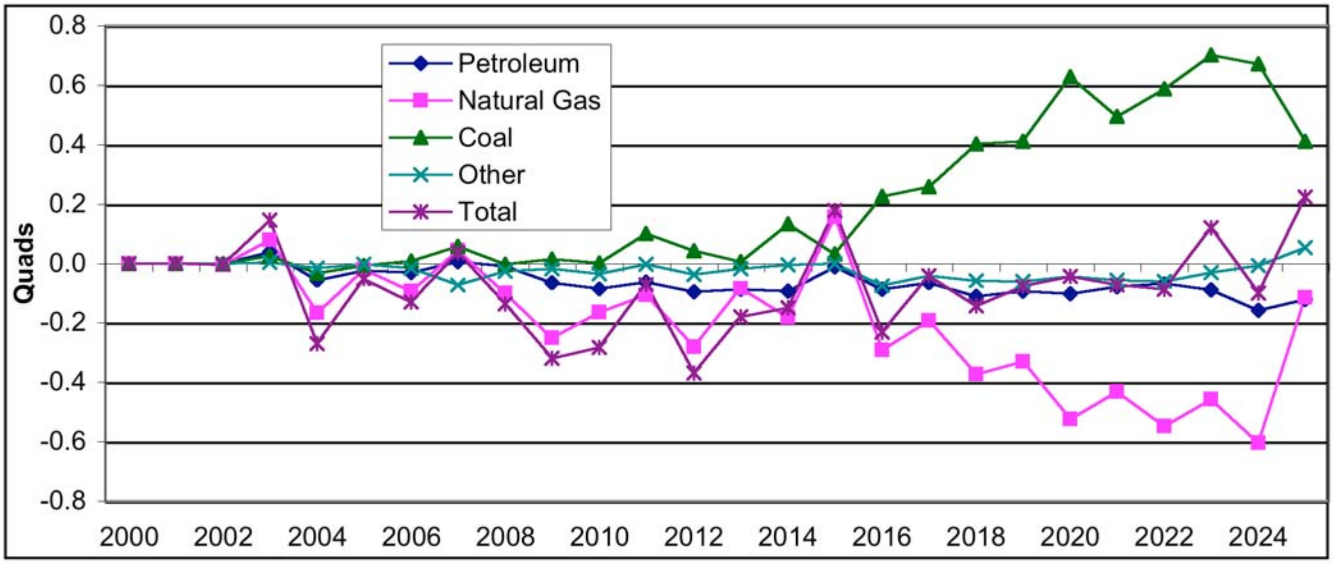
Figure 10. Change in national primary energy use for heating, cooling, other sectors, and total



The change in demands for energy will vary by the type of energy. Heating is provided by several energy sources such as natural gas, heating oil, biomass, as well as electricity. Cooling, however, is almost entirely provided by electricity, which can come from coal, nuclear, oil, gas, hydro, or renewable sources. An increase in cooling will increase the electricity demand, which in turn will increase the number of power plants built. Depending on the economics in the region of the country where the power is needed, different types of power plants will be called for. Cross-trading between regions will also influence the type and amount of plants added. As shown in Figure

11, nationally there is an increase in coal consumption and decrease in natural gas. The natural gas change is influenced both by the increase for electricity that is more than offset by the decrease for heating. The other fuels see relatively little change. Note that in 2025 energy use changes significantly. Figure 3 indicates that the PCM-IBIS data had temperatures dropping in that year (note the drop in average temperatures on the far-right of the first graph, especially in the northeastern regions). In such a situation, natural gas for heating would increase while coal use for electricity decline.

Figure 11. Change in national energy supply by fuel type



Net total electricity capacity increases by over 40 GW to meet the additional electricity requirements for cooling, with a change in the mix of technologies (Table 1). Most of the increase is in combustion turbines, which are quick to build and most useful for meeting peaking needs such as cooling requirements on hot days. Some gas-fired combined cycle, coal plants, renewable resources, and distributed generation are also added. While almost 80 GW of additional capacity is added, 39 GW of capacity are retired. These are mostly older gas or oil steam generators that become uneconomic due to price changes or operating capacity factors.

Table 1. Cumulative changes in electricity capacity by technology by 2025 (GW)

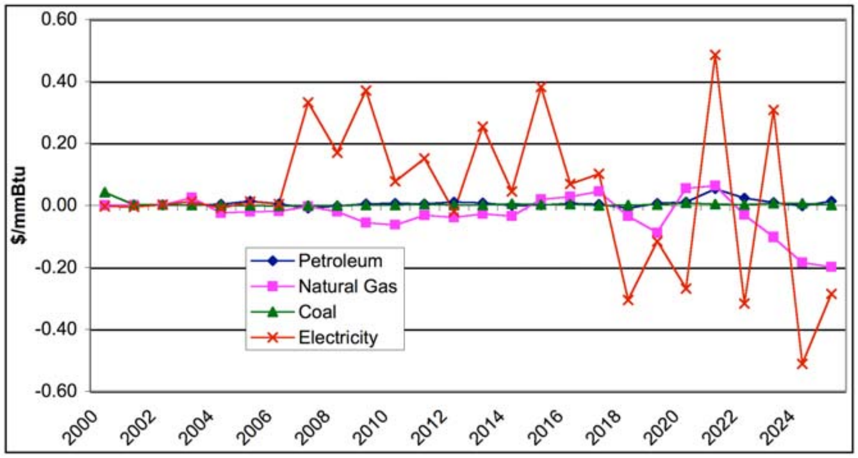
	Additions	Retirements	Net
Coal Steam	9.0	0.2	8.7
Other Fossil Steam	0.0	27.0	-27.0
Combined Cycle	5.6	0.7	4.9
Combustion Turbine/Diesel	60.5	11.1	49.4
Nuclear Power	0.0	0.0	0.0
Pumped Storage	0.0	0.0	0.0
Fuel Cells	0.0	0.0	0.0
Renewable Sources	3.2	0.0	3.2
Distributed Generation	1.3	0.0	1.3
Total	79.5	39.0	40.5

These changes may be accentuated by the methodology that DD-NEMS uses to add and retire capacity. It calculates capacity requirements by using a growth rate from the previous three years, but applies that to the most recent demand level. In the case of a high demand year, it will apply the growth rate to this high demand and decide that large amounts of capacity are needed quickly, meaning gas turbines. When demand dips, fewer plants are built and more expensive older plants, most notably gas or oil steam units, are unused and unprofitable for several years, leading to their retirement. This can be seen when comparing 2024 and 2025 results. By 2024, cumulative net additions were 57.8 GW, but since 2025 was a cool year in the PCM-IBIS data, total capacity did not grow much in that year while for the base case it did. As a consequence, the cumulative net increase by that year was only 40.5 GW. To some extent, this methodology actually reflects recent history, with a large expansion in gas turbines and combined cycle, followed by recent retirements, mothballing, and cancellations.

4. Cost Change

As mentioned above, DD-NEMS internally calculates the price for the various energy sources in each region based on input assumptions on supply quantities, technological change, and demand elasticity. Electricity prices are calculated using a wealth of information on existing and new power plant costs and electricity market structure, as well as the prices for different fuel types and contract terms. Figure 12 shows the difference in prices for the key fuels between the reference and varying-temperature case. Note that the electricity price fluctuates more than the others starting in 2007. This is likely due to the higher variability in electrical demand as well as changes in timing and types of power plants added, as described above. At the regional level, the electricity prices fluctuate even more widely, with price differences for some years on the order of $2/mmBtu (which translates to 0.7 ¢/kWh). There is some correlation with changes in regional cooling demands, but other factors influence prices as well.

Figure 12. National energy price differences between the base case and with varying temperatures



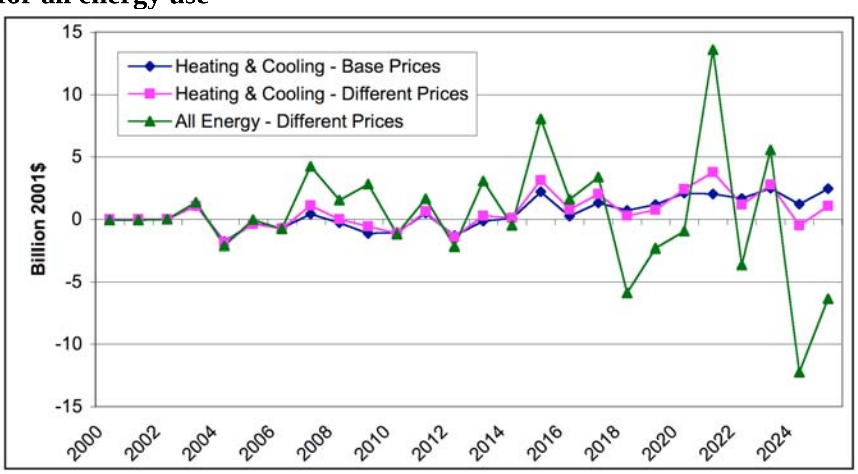
The cost for heating and cooling in each region is tied to the energy and price changes over time. Breaking the study period into an early and late, we see in the early years, pre-2015, the cost is generally low or negative since net energy use is less. In the later years though, energy costs are higher, especially for the southern regions (Table 2). New England and the E. N. Central regions have savings over the entire period. In all regions, costs are higher (or savings are lower) in the latter period, although temperature and price fluctuations will make individual years higher or lower. This increase in energy costs could have a broader impact on the economy of the country, but the changes are miniscule to the overall GDP and this analysis did not include the macro-economic modeling used by the full NEMS program.

Table 2. Change in heating and cooling cost for each region (million 2001$)

	2003-2014	2015-2025
New England	-417	-274
Mid Atlantic	-1485	130
E. N. Central	-3150	-1191
W. N. Central	-697	822
S. Atlantic	437	6489
E. S. Central	-20	3196
W. S. Central	716	3886
Mountain	186	643
Pacific	1547	3938
National	-2883	17641

Finally, while heating and cooling energy use may have significant changes due to the fluctuations in temperature (from –6% to +8% of heating and cooling energy as shown in Figure 7, Figure 8, and Figure 9), price changes will further modify the impacts on consumer bills. Figure 13 shows the heating and cooling cost changes when the same prices are applied to both cases and when the prices from each scenario are applied to each respective case. Applying the new prices to the energy used for all purposes (including non-heating and cooling) shows the role that other

Figure 13. National cost changes for heat and cooling end-use and for all energy use

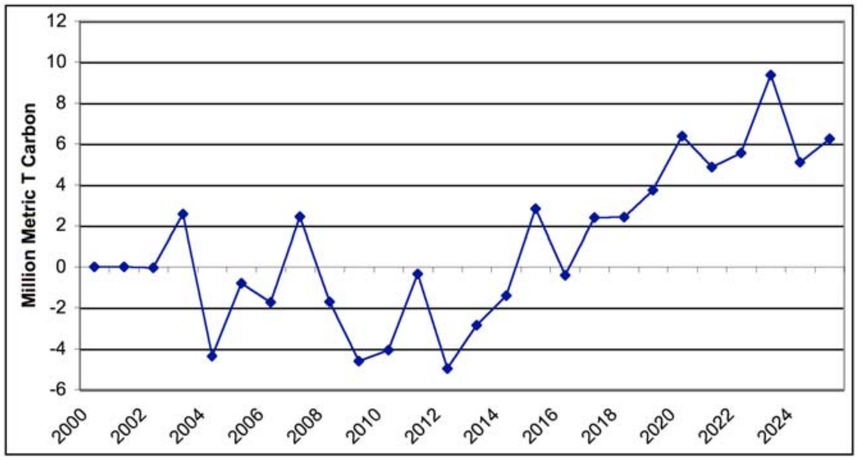


energy uses have in the over-all cost changes. Even though energy use for other sectors changed relatively little compared to heating and cooling (Figure 10), applying the regional price and demand changes results in much larger swings in total cost. These changes are most driven by the fluctuations in electricity prices, as well as the drop in natural gas prices in the last years of the study. Since DD-NEMS calculates these prices internally, it may be necessary to explore the algorithms used as regards to their response to temperature-induced demand changes.

5. Carbon Change

Lastly, with a change in energy use, both in type and quantity, the amount of carbon emissions will change. This change provides a small amount of feedback to global climate change. In the scenario examined, coal consumption increased and natural gas consumption decreased (Figure 11). Since coal is more carbon-intensive, the net impact was a small increase in carbon emissions (Figure 14) in the later years. The peak increase in 2023 of 9.4 million tonnes carbon represents 0.43% of total U.S. emissions for that year. Further, the trend shows a continuing increase in carbon emissions so the result of climate change could be a slight positive feedback in the postulated set of circumstances.

Figure 14. Carbon emission changes



6. Conclusions

The analysis conducted so far provides interesting insights into the interplay between climate change, energy use, and economics. While cooling needs increase energy use, heating needs reduce the amount. Since cooling (using electricity) is more inefficient than heating, the increase in primary energy use is amplified. Over time, the increase in cooling outweighs the decrease in heating leading to an overall increase. The variety of energy sources used for these services, the regional variation in energy requirements, and the market impacts on other energy consumption all combine to complicate the calculation of the net impact on the U.S. A trend of increased net energy use, cost, and carbon emissions are observed. Other economic changes such as prices may mitigate the increase, but with concomitant change to economic growth. Regional analysis shows a much larger impact in the southern regions of the U.S., while some northern regions have energy and cost savings.

The analytical tools used in this work could be improved to better refine the insights provided. A suite of climate simulations should be examined. The direct conversion of temperatures to degree-days using NCDC's weighting factors directly could improve accuracy. The Rosenthal paper suggests that the reference point for degree-days should be different than 65ºF. The effect of these changes on energy use sensitivity to temperature may be enlightening. The underlying NEMS model is continually being updated with better algorithms and input data, so the modifications we used here should be transferred to the most recent version for better analysis of variations in degree-days. There exists a variant of NEMS that extends to 2050. Applying the degree-day modifications to it could show results when temperature changes and consequent energy changes may be more dramatic. Finally, DD-NEMS is a very complex model. The addition of temperature-induced variations in energy demands may not be accurately accounted for in other algorithms and modules of the program. This should be further examined for accuracy and robustness. The results we have gathered so far in our analysis show that the interaction of climate and energy modeling can provide valuable insights to researchers and policymakers and should be continued.

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