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Quantifying the Impact of Proposed Carbon Emission Reductions on the U.S. Energy Infrastructure

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Quantifying the Impact of Proposed Carbon Emission Reductions on the U.S. Energy Infrastructure

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Abstract

The U.S. is actively considering the adoption of ambitious targets for greenhouse gas emissions that would require a reduction in energy-related carbon dioxide releases of 80% or more by the year 2050. Achieving such a goal will entail a rapid transition away from reliance on petroleum for transportation and high carbon fuels for electricity generation towards alternative transportation fuels and low-carbon electrical generating technologies, including solar, wind, geothermal, nuclear, and coal-fired generation with carbon capture and storage. Even with adoption rates for these technologies that are all near or even beyond the limits of plausibility, it will be impossible to achieve the desired emission reductions while simultaneously maintaining reasonable economic growth unless, in addition, the energy efficiency of the economy improves at a rate significantly above the historical trend.

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[1] This working paper supersedes MIT IPC Working Paper 09-004 (July 2009).

Introduction

This paper examines the implications for the U.S. energy infrastructure of the targets for greenhouse gas emission reductions now being actively considered by the U.S. government. The Waxman-Markey legislation recently passed by the U.S. House of Representatives calls for U.S. carbon emissions to decline 83% from their level in 2005 by 2050.[2] At various times President Obama has similarly called for emission reductions of over 80% by mid-century, and in July the President agreed with the other G8 leaders that the developed countries, including the U.S., should reduce their emissions 80% by 2050. These targets are loosely derived from integrated scientific and economic assessments of the consequences for the earth's climate of elevated atmospheric concentrations of greenhouse gases. The problem of mitigating greenhouse gas emissions will affect all countries. Here we examine what would be required for the U.S. to achieve reductions in this general range.

It is widely recognized that an effective strategy for reducing greenhouse gas emissions must focus on the energy sector, whose releases of carbon dioxide account for 80% of all U.S. anthropogenic greenhouse gas emissions.[3] There are two essential elements of a strategy for reducing energy-related carbon emissions: first, improving the efficiency of energy use (energy productivity) or, equivalently, reducing the 'energy intensity' of the economy; and second, 'decarbonizing' the nation's energy supply infrastructure – that is, reducing the carbon intensity of the energy system by moving away from primary reliance on petroleum for transportation and high carbon fuels for electricity generation towards alternative transportation fuels and low or zero-carbon electrical generating technologies. It is evident that these two elements of an overall strategy are interdependent. The more rapid the transition to low carbon energy supplies, the less we will need to rely on energy end-use efficiency gains to achieve a given emission reduction target, and vice versa.

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[2] H.R. 2454: American Clean Energy and Security Act of 2009, Section 702

[3] Climate change avoidance strategies must also reduce emissions of potent non-carbon greenhouse gases such as methane and nitrous oxide.

There is in fact a fixed relationship between the two if a target for economic output is specified together with the carbon reduction goal. The relationship between these four factors – carbon emissions, carbon intensity of the energy system, energy intensity of the economy, and economic output – is given by the simple identity[4]

$$C = \left(\frac{C}{E}\right) \times \left(\frac{E}{Y}\right) \times \left(\frac{Y}{P}\right) \times P \qquad (1)$$

where C = carbon emitted in a given time period, E = energy consumed in that time period, Y = economic output, and P = population, and where, for convenience, economic output is expressed as output per capita. This ratio, Y/P, is the broadest measure of productivity in an economy, and in the long run is the single most important determinant of national prosperity. Equation (1) applies to any specified geographical unit, from a small region to a country to the world as a whole. The differential form of the identity relates the rate of change of carbon emissions to the rate of change of each of the four factors, i.e., carbon intensity, energy efficiency, economic productivity, and population:

$$\frac{\partial C}{C} = \frac{\partial (C/E)}{(C/E)} + \frac{\partial (E/Y)}{(E/Y)} + \frac{\partial (Y/P)}{(Y/P)} + \frac{\partial P}{P} \qquad (2)$$

Alternative and even simpler differential forms are

$$\frac{\partial C}{C} = \frac{\partial (C/Y)}{(C/Y)} + \frac{\partial (Y/P)}{(Y/P)} + \frac{\partial P}{P} \qquad (2a)$$

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[4] The relationship between these factors was first pointed out by the Japanese engineer Yoichi Kaya (Kaya, Y., “Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios”, Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, 1990 (mimeo).)

$$\frac{\partial C}{C} = \frac{\partial (C/E)}{(C/E)} + \frac{\partial (E/P)}{(E/P)} + \frac{\partial P}{P} \qquad \text{(2b)}$$

where (C/Y) indicates the carbon use per unit of economic output, and (E/P) is the energy use per capita.

As equation (2) indicates, it is a straightforward exercise in carbon, energy, and economic growth accounting to identify energy efficiency and decarbonization scenarios that could, in combination, meet specified targets for carbon emission reduction and economic growth. In this paper we present a simple model for investigating these scenarios for the U.S. economy over the period from 2008 to 2050. Details of the model are provided in the Appendix and the results are discussed below. These results come with an important proviso. Whether any scenario satisfying the basic identity could actually be realized in practice cannot be determined from this kind of exercise, since this depends upon interactions between the energy sector and the rest of the economy that require much more complex modeling to describe. But the identity is nonetheless useful in indicating possible pathways towards achieving the various emission reduction goals and in suggesting the scale of the change needed to reach them. Equally important, it shows what is <u>not</u> possible, and as such is useful in revealing plans and strategies that are incapable of achieving their intended result.

Scenarios

In this paper we take as the target for aggregate U.S. energy-related carbon emissions in 2050 an 85% reduction relative to the 2005 level. This is slightly above the Waxman-Markey goal and is equivalent to an 80% reduction relative to U.S. emissions in 1990 – a goal that has been advocated by President Obama and others in the past. It corresponds to an average rate of reduction in carbon emissions of 4.18% per year.

We next consider three alternative decarbonization scenarios, described below. The scenarios cover the entire economy, but the short descriptions focus on the electric power sector.

Scenario 1 ("All Hands on Deck"): In this scenario, the electricity sector in 2050 relies to a much greater extent than today on low carbon sources of supply. Solar and wind expand rapidly, and by 2050 each is providing 20% of total electricity supply. The obstacles that would today stand in the way of such a scenario are assumed to be overcome; reliability problems associated with heavy dependence on these intermittent sources are resolved with economic electricity storage and other advanced grid technologies that are not available today. Nuclear is also assumed to provide 20% of total electricity supply (the same percentage as today, but with many more reactors producing much more electricity in absolute terms). The technology for coal plant carbon capture and sequestration (CCS) is assumed to be available without constraint. Geothermal provides 100 GWe (compared with about 2 GWe today). Hydroelectric plants continue to contribute at their current, relatively modest level. These are generally very ambitious goals. Some observers would likely regard them as being at or even beyond the bounds of plausibility.

Scenario 2 ("No Nuclear/No Coal"): In this scenario, the path to decarbonization is diverted by obstacles to nuclear and coal use. No new nuclear plants are built, and all currently operating plants are phased out. Carbon capture and sequestration technology is assumed not to become available, and no new coal plants are built either. Existing coal plants are phased out. Solar and wind expand rapidly, however; by 2050 each are providing 20% of total electricity supply. The balance of electricity supply is provided by a combination of hydroelectricity (unchanged from today), geothermal (100 GWe), and biofuel.

Scenario 3 ("Additionally Constrained"): In this scenario, the constraints on low-carbon sources multiply. As in Scenario 2 nuclear and coal are phased out completely, while wind and solar are more restricted than in the two previous scenarios. Wind accounts for 15% of total electricity supply in 2050, and solar another 5% – both many times larger than their current contributions, but below today’s most optimistic projections. Hydro, geothermal, and biofuel provide the balance of electricity supply.

The three scenarios are summarized in Table 1.

Table 1: Decarbonization Scenario Assumptions

	SCENARIO 1 “All Hands on Deck”	SCENARIO 2 “No Nuclear/No Coal”	SCENARIO 3 “Additionally Constrained”
Population growth	0.9%/yr	0.9%/yr	0.9%/yr
Intermittent renewables as a share of total electricity generation in 2050 (wind/solar)	40% (20%/20%)	40% (20%/20%)	20% (15%/5%)
Carbon capture and sequestration in 2050	Limited only by C emission constraint	None	None
Nuclear as a share of total electricity generation in 2050	20%	None	None
Geothermal in 2050	100 GWe	100 GWe	100 GWe
Hydroelectric	Same as today	Same as today	Same as today

‘Business-as-usual’ in energy efficiency means severely constrained economic growth

To see what these different decarbonization scenarios would mean, we first consider the case in which the energy intensity of the economy continues to decline at the same rate, 2.16%/year, that it has averaged over the past 25 years.[5] From equation (2), the combined rate of decarbonization (C/E) and economic growth (Y/P) required to achieve the targeted reduction in carbon emissions in this case is:[6]

$$\frac{\partial(C/E)}{(C/E)}+\frac{\partial(Y/P)}{(Y/P)}=-4.18+2.16-0.90=-2.89\%/yr$$

Table 2 shows the economic growth trajectories associated with each of the three decarbonization scenarios. Even in the "All Hands on Deck" scenario, with its very optimistic assumptions about the future availability of renewables, nuclear, and CCS, the mid-century carbon emission reduction goal could only be achieved if the annual rate of growth in GDP per capita between now and 2050 were to decline to 1% per year. It is worth noting that in no decade since the 1930s has this broad measure of the nation's economic growth performance been as low. For the less optimistic "No Nuclear/No Coal" and "Severely Constrained" scenarios, per capita economic output would actually have to contract in order to achieve the mid-century carbon emission reduction goal.

Table 2: Economic Growth with 'Business-as-Usual' Energy Efficiency Trend

Supply-Side Scenario	Growth rate in GDP/capita, 2008-2050
"All Hands on Deck"	+1.0%/yr
"No Nuclear/No Coal"	-0.67%/yr
"Severely Constrained"	-0.85%/yr

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[5] This is the emission-weighted average performance for the economy as a whole. Our model disaggregates this economy-wide average into the average trend for each of the energy-using sectors: transportation (-1.53%), residential (-2.66%), commercial (-1.76%), and industrial (-3.03%).

[6] The U.S. population is assumed to grow at an annual rate of 0.9% between now and 2050, following the estimate of J.S. Passel and D'Vera Cohn, "U.S. Population Projections: 2005-2050", Pew Research Center Report, February 2008. The U.S. Census Bureau recently projected a growth rate of 0.8% per year over this period (http://www.census.gov/population/www/projections/usinterimproj/).

Uncompromising environmental advocates assert that the risks of climate change are so great that carbon emission reductions must be achieved regardless of what this would mean for economic growth. But that view is not widely shared and as a practical matter national policy is unlikely to privilege the emission reduction goal in this way. Certainly many people would regard the prospect of weak or even negative economic growth in the service of avoiding global climate change as unacceptable. But it is an inescapable fact that even with extraordinary measures to adopt low-carbon energy supply technologies on a large scale it will be mathematically impossible for the country to enjoy even moderate economic growth in the absence of much stronger energy efficiency gains than in the past. Equally, strong economic growth will be impossible even with rapid gains in energy efficiency if these are not accompanied by much more aggressive rates of decarbonization.

We next explore the implications for the energy system of setting a requirement for more vigorous economic growth simultaneously with the desired carbon emission reductions.

‘Business-as-usual’ in economic growth means ‘NOT-business-as-usual’ in energy supply and demand

We specify a performance goal for the U.S. economy of 2% annual growth in GDP per capita through 2050. In historical terms, this is a fairly modest target. It is approximately equal to the per capita growth performance achieved by the U.S. economy between 1973 and 2000, and falls well below the 2.5% growth rate achieved between 1950 and 1973 (and again during the strong expansion years of 1992-2000).[7] As before, we impose the 85% carbon emission reduction target in 2050, and again consider the three decarbonization scenarios described above.

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[7] Between 2000 and 2007, a period of weak growth that preceded the current economic recession, the per capita U.S. growth rate was 1.35%/year.

The results are summarized in Table 3. An important result is the required rate of reduction in energy intensity, i.e., energy use per unit of economic output (E/Y). In Scenario 1 (“All Hands on Deck”), with its highly optimistic assumptions about the rate of decarbonization, energy use per unit of economic output would need to decline by 3.05%/year on average between now and mid-century in order to achieve the carbon mitigation and economic growth goals. As already noted, energy use per unit of GDP declined by 2.16%/year on average between 1980 and 2006; from 1996-2006 the average rate was 2.52%/year. In Scenario 2 (“No Nuclear/No Coal”), with its less optimistic assumptions about the availability of low-carbon technologies, energy use per unit of economic output would need to decline by 4.50%/year. In Scenario 3 (“Additionally Constrained”), with its even less optimistic assumptions, the implied requirement is for energy efficiency to improve by 4.75%/year on average. In each scenario total energy use in 2050 would be lower than it is today -- by 6.1% in the “All Hands on Deck” scenario, and by more than 50% in the “Additionally Constrained” scenario.

In the ”All Hands on Deck” scenario, the reduction in carbon emissions is achieved primarily through very rapid electrification of the economy, which by 2050 relies on electricity for 54.3% of final energy use compared with 18.3% today. In the ”No Nuclear/No Coal” and “Additionally Constrained” scenarios electrification is much less important, and the main contributor to carbon emission reductions is a dramatic reduction in energy use. In all three scenarios, however, rapid electrification of the automobile fleet is essential, even assuming the early availability of advanced biofuel with a much lower carbon footprint than corn ethanol.[8]

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[8] In our model, biofuels are assumed to have a carbon emissions rate in 2050 equal to 50% that of traditional petroleum fuels.

Table 3: Scenario Results

	SCENARIO 1 "All Hands on Deck"	SCENARIO 2 "No Nuclear/No Coal"	SCENARIO 3 "Additionally Constrained"
Rate of change of CO_2 emissions per unit of GDP, 2008-2050	-7.08 %/yr	-7.08 %/yr	-7.08 %/yr
Rate of change in energy consumption per capita, 2008-2050	-1.05 %/yr	-2.50%/yr	-2.75 %/yr
Rate of change in energy consumption per dollar of GDP, 2008-2050	-3.05 %/yr	-4.50%/yr	-4.75 %/yr
Change in total U.S. final energy use between 2008 and 2050	-6.1%	-48.3%	-53.5%
Change in total U.S. electricity consumption between 2008 and 2050	+178%	-25.0%	-43.6%
Share of electricity in final energy use (cf. 18.3% in 2008)	54.3%	26.6%	22.2%
Transportation sector end use energy consumption in 2050	33% biofuel 67% electric 0% petroleum	54% biofuel 46% electric 0% petroleum	60% biofuel 40% electric 0% petroleum

The implication of these results is clear: the past performance of the U.S. energy sector with respect to both energy efficiency gains and decarbonization falls far short of what will be required in the future. It will be impossible to achieve the mid-century carbon emission reduction goal while at the same time maintaining a decent rate of economic growth without major advances in both dimensions of performance relative to past trends (see Figure 1).

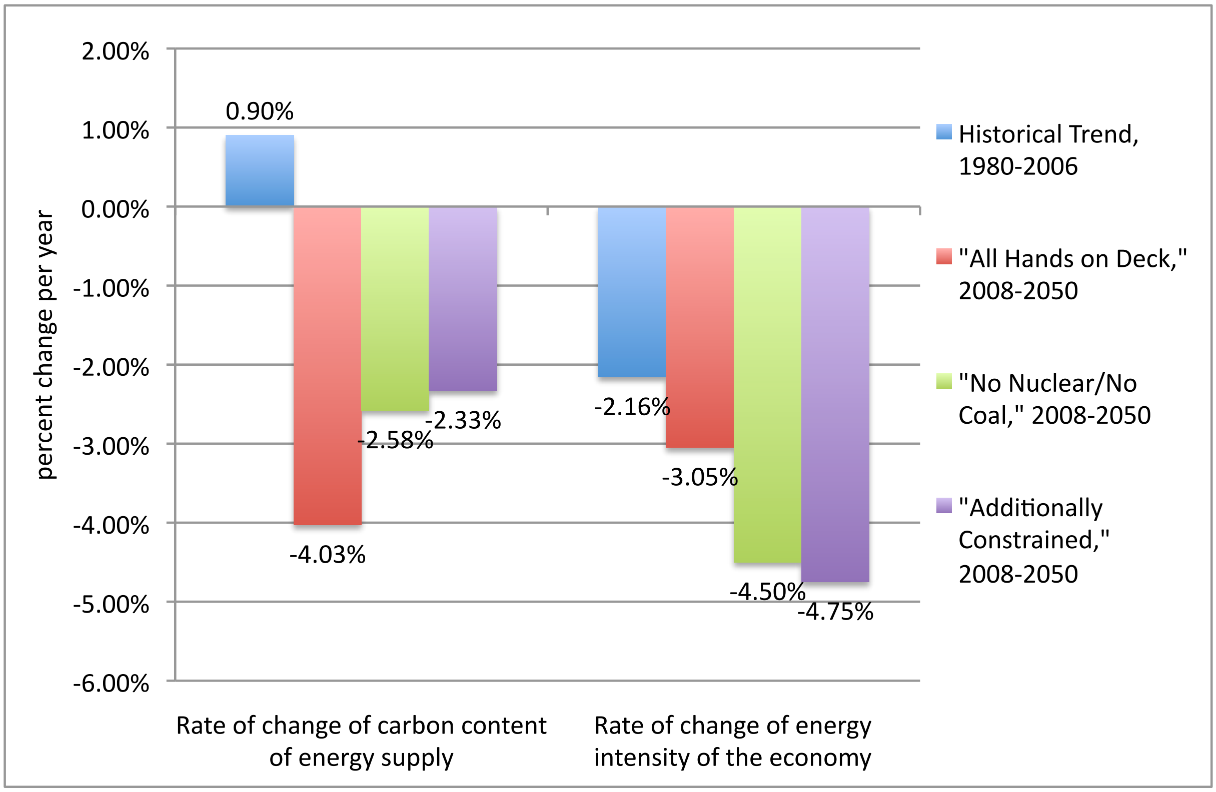

Figure 1: Rates of decarbonization and energy efficiency improvements required by each scenario

How difficult will it be to meet these requirements? We can gain insight into the energy efficiency requirement by estimating the needs within individual energy end-use sectors and comparing these with recent performance. Figure 2 shows the recent historical trend in energy efficiency in each of the four main end-use sectors of the economy, i.e., transportation, residential buildings, commercial buildings, and industry.[9]

As one example, consider the residential buildings sector.

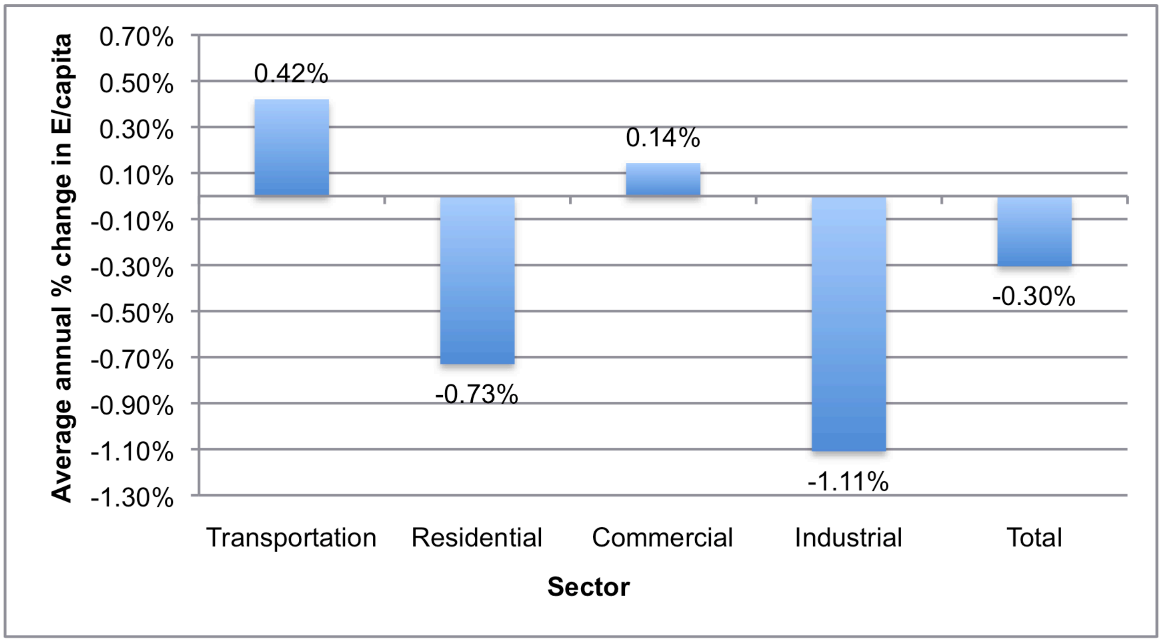

Figure 2: Average annual rate of change in final energy use per capita, by end use sector, 1980-2006

Figure 3 compares the projected residential energy efficiency requirements for each of the three decarbonization scenarios with the actual 25-year historical trend in residential energy efficiency (expressed in terms of reductions in energy use per capita) in several states. The variation in performance across the states is striking. Many factors have contributed to this variation, including significant differences in state-level energy efficiency policies.

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[9] In our model we estimate the energy efficiency requirement in each sector using the predictions of the Energy Information Administration’s *2009 Annual Energy Outlook* (AEO2009). For each sector, we compute the ratio of sector-specific to economy-wide energy intensity trends in AEO2009 for the period from 2008 to 2030, and these same sector-to-average ratios are used in our model. They are: residential: 1.17; commercial: 0.87; industrial: 1.03; transportation: 0.94.

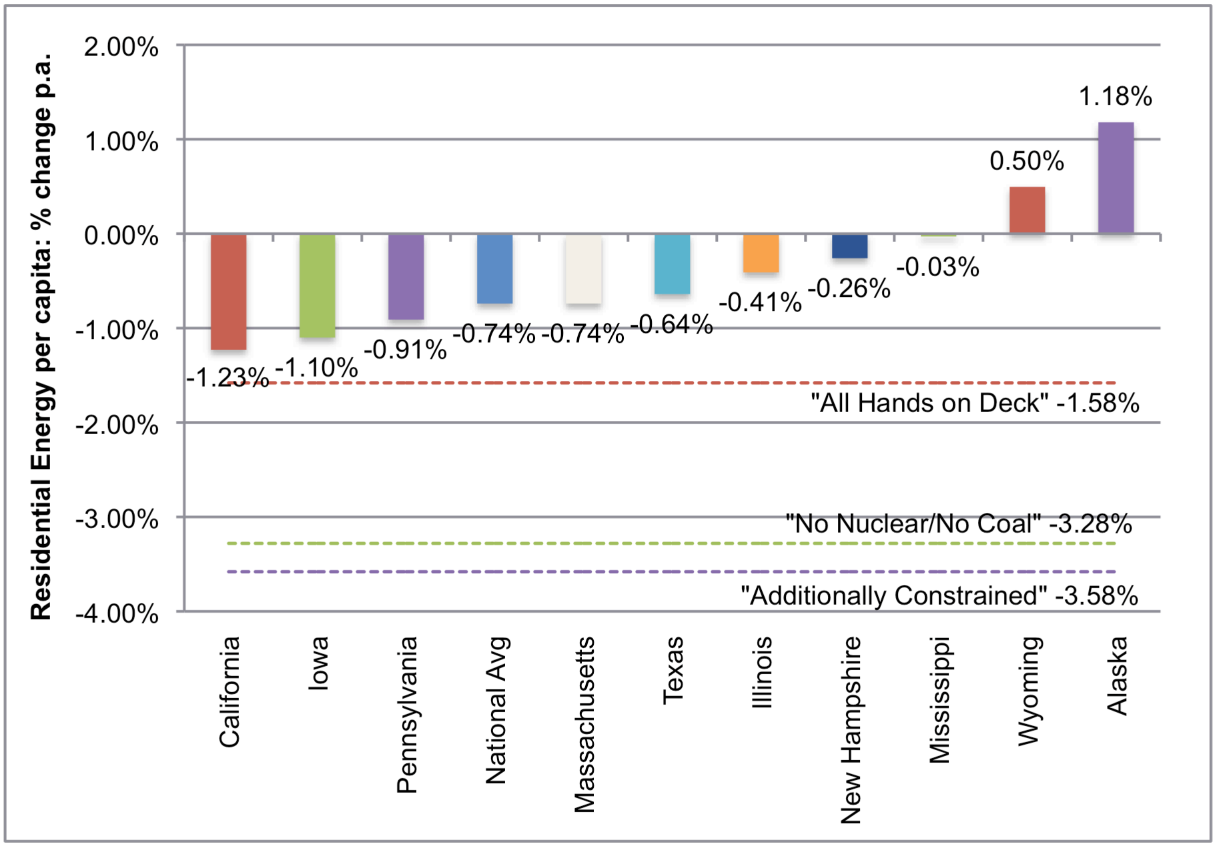

Figure 3: Average annual change in residential energy use per capita (%/yr), 1980-2006

For the “All Hands on Deck” scenario, one way to achieve the required gains in residential energy efficiency at the national level would be for every state to raise its performance above the level of the best recent performers (i.e., California and Iowa.) For the “No Nuclear/No Coal” and “Additionally Constrained” scenarios, however, even this would fall far short of the need; in those cases, every state would have to raise its performance to a level nearly three times that of California’s recent record.

The decarbonization requirements on the supply side of the energy infrastructure are no less formidable. Focusing again on the implications for the electric power sector, in the “All Hands on Deck” scenario we estimate that the average rate of installation of all new generating capacity would be about 120,000 MWe per year. (This is almost certainly an underestimate since our simple model makes no allowance for the need for an adequate capacity reserve margin to maintain adequate grid reliability levels.) As Figure 4 shows, this is roughly twice the installation rate during the peak year for new capacity additions during the past decade, and several times higher than the installation rate during more typical years. Figure 5 shows the shares of installed capacity in 2050 by technology in this scenario. Even though wind and solar are assumed to be supplying amounts of energy comparable to nuclear and coal, the capacity requirements for these technologies are much greater because of their inherently low capacity factors. [10]

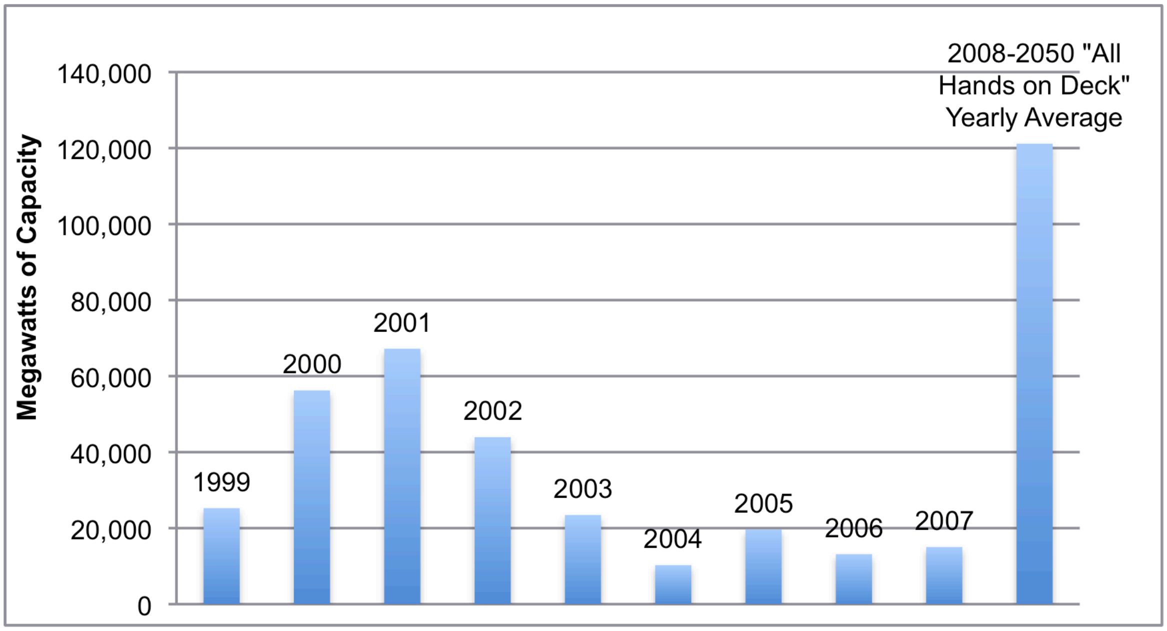

Figure 4: Additions of U.S. electrical generating capacity of all types: 1997-2007 (actual), and 2008-2050 (projected in “All Hands on Deck” scenario)

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[10] Of course, even in the absence of the climate constraint there would also be a large requirement for new capacity, to meet additional electricity demand and to replace retired capacity.

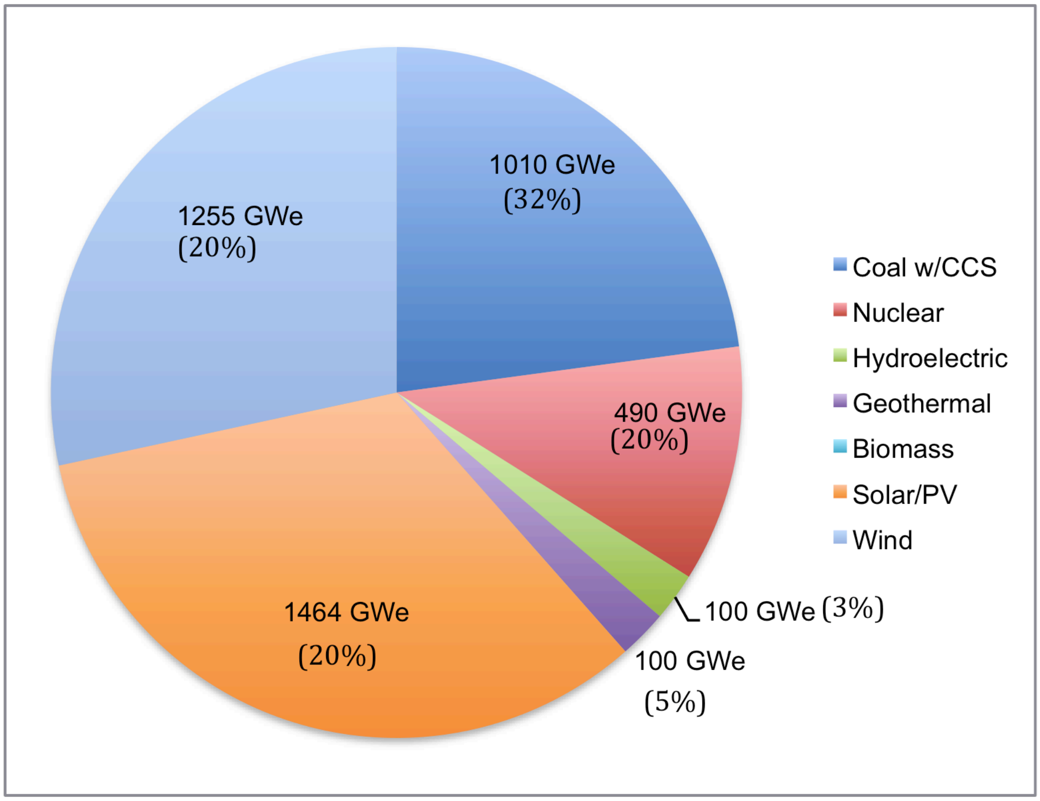

Figure 5: Total Installed Electrical Generating Capacity in 2050 for the "All Hands on Deck" scenario (% share of electricity generation in parentheses)

Demand-response programs enabled by new 'smart-grid' technologies could potentially reduce this capacity requirement. The main purpose of these programs is to shave and shift in time the peak power demand that must be met by regional electricity networks. Such measures are expected to be less expensive than installing low-carbon capacity sufficient to meet daily and seasonal demand peaks. One recent study found that demand-response programs could conceivably bring about a reduction of 20% in peak demand by the year 2019. Here we make a simple estimate of the potential impact of such programs on the requirements for new capacity through 2050. In the "All Hands on Deck" scenario, a demand-response strategy that lowered the peak-to-average demand ratio from its current value of 1.75 for the U.S. as a whole to, say, 1.25 by the year 2050 (i.e., a 28% reduction in peak demand) would avoid the need to build 288 GWe of coal with CCS, 140 GWe of nuclear, 28

GWe of geothermal, 416 GWe of solar, and 356 GWe of wind between 2008 and 2050.[11] Taken together this represents more than the total installed nameplate electricity generating capacity in the U.S. today.

The role of natural gas: Natural gas plays only a modest role in our scenarios. In most applications it is displaced by advanced biofuels, which emit less CO_2 per unit of energy output. Recent advances in drilling technology promise to increase greatly the amount of gas that is economically recoverable from shales.[12] This has led to suggestions that natural gas may hold the key to the energy transition, either as a bridge fuel or in the longer-term as a complement to intermittent renewables.[13] Of course, from the perspective of carbon emissions natural gas is not a ‘clean’ fuel, although it emits significantly less carbon dioxide per unit of energy than coal. If combined with carbon capture and storage, natural gas could be an alternative to the large scale use of coal in the electric power sector, though many of the economic and other obstacles that stand in the way of implementing CCS with coal-fired power would apply in this case too.[14] In the absence of CCS, natural gas could only serve as a short-term bridge fuel, and from a carbon emissions perspective it would be less attractive than advanced biofuels, for which it might otherwise substitute.

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[11] For this simple calculation we assume that each type of generation contributes to meeting the peak demand in the same proportion that it contributes to meeting energy requirements.

[12] The Potential Gas Committee’s 2008 year-end report estimates that the U.S. has a total available future supply of 2,074 Tcf, up 35% from just two years earlier (see http://www.mines.edu/Potential-Gas-Committee-reports-unprecedented-increase-in-magnitude-of-U.S.-natural-gas-resource-base)

[13] See, for example, John E. Podesta and Timothy E. Wirth “Natural Gas: A Bridge Fuel for the 21st Century”, Center for American Progress, August 10, 2009.

[14] Even with the recent additions, the latest estimate of total technically recoverable natural gas is still several times lower than current estimates of total recoverable coal resources. If natural gas with CCS were to replace coal with CCS at the rate of use envisaged in 2050 in the “All Hands on Deck” scenario, the estimated total future U.S. supply of 2,074.1 trillion cubic feet (see footnote 12) would be exhausted within 50 years.

Conclusions

Officials in both the executive and legislative branches of the U.S. government have declared their support for the goal of reducing U.S. carbon emissions by 80% or more by 2050. At the upcoming U.N. Climate Change Conference in Copenhagen in December the U.S. may commit to such a goal as part of what is expected to be the follow-on to the first phase of the Kyoto Protocol, which expires in 2012. This analysis has examined some of the implications of achieving a goal of this magnitude for the U.S. energy sector and for the economy more generally.

In essence, the recent energy efficiency and decarbonization performance of the U.S. economy falls far short of what would be required to achieve the goal. One indication of the size of the task ahead is that if the energy intensity of the economy were to continue to decline at the same rate as during the last 25 years, the economy could not grow faster than roughly 1% per year per capita between now and mid-century, even with extraordinarily high rates of installation of solar, wind, geothermal, nuclear and coal-fired generating capacity with carbon capture and storage. And if the economy were to grow instead at a more acceptable (but still relatively modest) rate of 2% per year per capita, even heroic decarbonization measures would fail to yield the desired emission reductions unless, in addition, the country were to move onto a path of rapidly declining energy intensity and remain on that path for decades. Since most of the low carbon energy supply technologies are more expensive than the incumbent high-carbon energy sources, this analysis also draws attention to the need for a sustained flow of innovations in many different fields of application in order to bring down the costs of these low-carbon alternatives.

Appendix

To investigate the implications of adhering to alternative carbon emission reduction goals, a simple model based on the differential form of the basic identity

$$C = \left(\frac{C}{E}\right) \times \left(\frac{E}{Y}\right) \times \left(\frac{Y}{P}\right) \times P$$

is applied to the energy use of the U.S. economy between 2008 and 2050. Actual U.S. energy use in the base year of 2007 is broken down by sector and by fuel, as shown schematically in Table A.1. Carbon emissions are calculated based on the 2006 CO_2 emission factors for each fuel/sector combination reported by the Energy Information Administration, with the exception of biofuels, which are assumed to have emissions 50% below those of transportation petroleum fuels.[15] The emission factors for biofuels are a subject of considerable debate, with published estimates ranging from twice the rate of emissions from gasoline to net negative emissions.[16] The biofuels emissions factor assumed here is intended to serve as a conservative estimate of what might be achievable in the near term. “Electricity” in the residential, commercial, industrial, and transportation sectors does not contribute to those sectors’ CO_2 emissions, as electricity-related emissions are accounted for separately in the electric power sector. The emission factors used in the model are shown in Table A.2.

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[15] “Carbon Dioxide Emission Factors (1980-2006)” Energy Information Administration. http://www.eia.doe.gov/oiaf/1605/ggrpt/excel/CO2_coeff.xls

[16] See, for example: Timothy Searchinger, Ralph Heimlich, R.A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes, Tun-Hsiang Yu “Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change”, *Science* Vol. 319, February 29, 2008; Environmental Protection Agency “EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels” EPA-420-F-09-024, May 2009 http://www.epa.gov/oms/renewablefuels/420f09024.pdf;
Delucchi, Mark A. “Lifecycle Analysis of CO_2-Equivalent Greenhouse-Gas Emissions from Biofuels”, presentation at the Conference on Modelling Global Land Use and Social Implications in the Sustainability Assessment of Biofuels, Copenhagen, Denmark, June 4-5, 2007.

Table A.1: Sectors and Fuels in Model

Sector	**Fuel**
Residential	Petroleum
	Natural Gas
	Coal
	Biofuel
	Geothermal
	Solar/PV
	Wind
	Electricity
Transportation	Petroleum
	Natural Gas
	Biofuel
	Electricity
Industrial	Petroleum
	Natural Gas
	Coal
	Coal w/CCS
	Nuclear Heat
	Biofuel
	Geothermal
	Solar/PV
	Wind
	Hydro
	Electricity

Sector	**Fuel**
Commercial	Petroleum
	Natural Gas
	Coal
	Biofuel
	Geothermal
	Solar/PV
	Wind
	Electricity
Electric Power	Petroleum
	Natural Gas
	Coal
	Coal w/CCS
	Nuclear
	Hydro
	Geothermal
	Biofuel
	Solar/PV
	Wind
	Imports

Table A.2: Default Emission Coefficients in Model

Fuel	Emission Coefficient (Million metric tons CO_2 per quadrillion Btu)
Petroleum – Transportation	70.55
Petroleum – Industrial	74.54
Petroleum – Commercial	83.58
Petroleum – Residential	77.21
Petroleum – Electric Power	84.10
Biofuel	35.44
Natural Gas	53.06
Coal	94.70
Coal with Carbon Capture (90%) and Sequestration	9.47
Geothermal	1.31
Wind	-
Solar	-
Nuclear	-
Hydroelectric	-

Key inputs to the model are shown in Table A.3. The model assumes that energy demand in each sector grows at the same overall rate. A further assumption is that each sector must reduce its carbon emissions by the same overall percentage. In each sector the mix of fuels is calculated such that the sector's CO_2 limit is not exceeded. In the transportation sector, biofuel is the next lowest-emission fuel after electricity, and fuel demand is met with biofuel until the CO_2 limit of that sector is reached. The remainder is allocated as electricity. In the commercial and residential sectors, natural gas is used to supply the allowable carbon-emitting energy, and then geothermal heat and electricity provide the rest. In the industrial sector, biofuel provides the carbon-emitting energy, and geothermal heat and electricity again fill the balance. The required electricity supply to each sector (augmented by a transmission and distribution loss factor) is summed over all sectors and this determines the total electricity supply. The mix of fuels to the electric power sector is then determined consistent with the scenario assumptions such that its permitted CO_2 emissions are not exceeded.

Table A.3: Key Inputs for Model

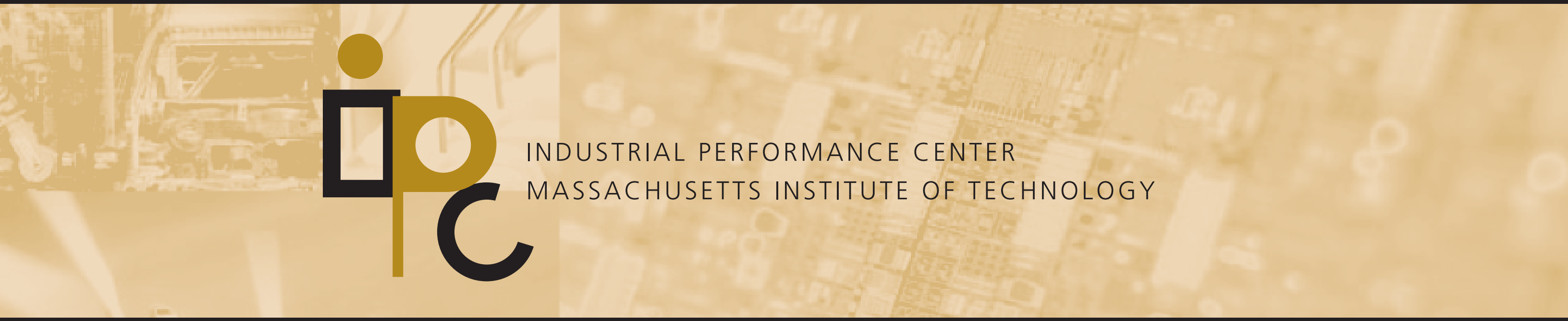
Rates of Change (% per year)	Population GDP per Capita Energy Intensity of GDP
CO_2 Reduction Goal	% reduction of CO_2 emissions Base year for CO_2 comparison (1990, 2000, 2008) End Year (2050 considered here)
Emissions Factors	CCS capture efficiency (%) CO_2 reduction for biofuel versus petroleum
Other	Contribution of each fuel to the energy generation for each sector Peak to average power demand ratio

Once the fuel mix has been determined for the electric power sector, the model calculates the equivalent installed capacity required to meet the electricity demand in that year, based on realistic or historical capacity factors and thermal-to-electric conversion factors, as well as an assumed peak-to-average power demand ratio. The capacity factors used for this analysis are given in Table A.4. The peak power demand is set at 175% of the average demand in the base case, which implies that installed capacity must be enough to supply 175% of the average demand. This requirement is spread among technologies proportional to their contribution to total electricity generation. This distribution would almost certainly not be the optimal way of meeting peak demand, but further study on the use of renewables and energy storage to satisfy peak power demand is needed to assess this situation more fully. The model subsequently calculates the required installation rate for the intervening years for a number of the technologies, where the starting years for installing nuclear and coal with carbon capture and sequestration are adjustable.

Table A.4: Default Capacity Factors in Model

Electric Power Source	Capacity Factor
Coal	73%
Coal with Carbon Capture and Sequestration	70%
Nuclear	90%
Hydroelectric	42%
Geothermal	90%
Solar/PV	30%
Wind	35%

This model is a simple representation of energy-related CO_2 emissions, and does not model interactions between policies, the energy system, and the economy as a whole. As such, it is not appropriate for predicting how a policy will affect the U.S. economy and energy system in practice, but rather is a useful tool for exploring possible energy pathways for meeting emission goals, and for revealing pathways that cannot meet those goals.



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