# Supporting Information: Effectiveness of a Segmental Approach to Climate Policy

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# 1 Modeling Technology Portfolios

## 1.1 US Model

We begin by investigating whether the goal of generating 80% of electricity with clean technologies by 2035 can be consistent with the earlier objective set by the US to reduce emissions to 80% below 1990 levels by 2050. Carbon dioxide equivalent emissions from electricity at a given point in time, $t$, can be expressed as [16]:

$$C_t = GDP_t \times e_t \times c_t = E_t \times c_t \tag{1}$$

where emissions ($C$) are the product of GDP, electricity intensity of the economy ($e = E/GDP$) and the carbon intensity of electricity ($c$). By constraining emissions to be consistent with climate targets, and investigating a high and low efficiency scenario for electricity consumption, we derive a target for carbon intensity of electricity. This target is then used to study technology portfolios that would meet climate goals.

We assume an emissions trajectory for US electricity that reduces emissions to 80% below 1990 levels by 2050 (this is 83% below 2005 levels by 2050). We also meet the shorter term emissions reduction goals outlined by President Obama of 17% below 2005 levels by 2020, 30% below 2005 by 2025, and 42% below 2005 by 2030 [23]. Emissions targets in other years are estimated by linear interpolation.

The goal of 80% reductions in emissions below 1990 levels by 2050 was set by G8 nations to be in accordance with limiting global warming to 2°C [15, 18]. But this 2050 target may be on the lower end of that needed from Annex I countries to adhere to a path consistent with a stabilization level of 450 ppm $CO_2$eq; and in the shorter term significantly more aggressive targets may be needed than those outlined above [9]. The 450 ppm stabilization level was found to be consistent with a less than 2°C global mean temperature increase in roughly 50% of the model runs assembled by the IPCC [26].

To derive an emissions trajectory for electricity, we allocate 39% of the total emissions to this sector based on levels in recent years [12]. To follow the emissions trajectories outlined, an equal percent reduction in carbon emissions is needed across all energy demand sectors[1].

We then build high and low demand-side efficiency (energy-efficiency) scenarios. These are based on a medium GDP growth projection from the IPCC (corresponding to B2), which has been downscaled from North America to the US [14], and a constant annual percent decrease in electricity intensity of economic growth (2010 values are corrected using recent data [11, 22].)

The low-efficiency scenario is derived from EPRI's baseline electricity consumption projection to 2030 [13]. We assume a baseline rate for decreasing energy intensity of -0.9% per year and extend this to 2050 [13]. (2010 values are corrected using recent data [11, 22].) The baseline rate was also confirmed using historical data over the past 6 years[2] [11, 22]. Because the baseline assumes an extension of historical decreases in energy intensity, it predicts significant energy savings. The increase in electricity consumption between 2010 and 2035 is 25%, and between 2035 and 2050 is 22%. In 2010 the assumed electricity consumption is 14.2 EJ; in 2035 it is 17.8 EJ; and in 2050 it is 18.2 EJ.

The high efficiency scenario was derived from an EPRI estimate for the maximum achievable potential savings to 2030, and a resumption of the baseline rate from 2030-2050 [13]. The high efficiency scenario follows a decrease in energy intensity of -1.5% annually to 2030, then -0.9% annually to 2050. This is consistent with the qualitative observation of decreasing returns in a recent meta-analysis [5], which found that demand-side efficiency studies over shorter time horizons predicted higher annual percent improvements than those over longer time horizons. The increase in electricity consumption between 2010 and 2035 is 10%, and between 2035 and 2050 is 22%. In 2035 the assumed electricity consumption is 15.7 EJ; and in 2050 it is 16.0 EJ.

For comparison, our high efficiency trajectory to 2050 saves, relative to the baseline, roughly two times the EPRI maximum achievable potential savings to 2030 [13]. (The length of our time horizon is twice that of EPRI.) Other studies found comparable potential savings to this EPRI study [5, 25]. A study by McKinsey & Company is an outlier in that it focuses on a single year (2020), and projects more than twice the savings of the EPRI report in that year[3] [7, 6].

The carbon intensity target (as a function of time) is then used to constrain supply-side portfolios. In 2035, 20% of electricity consumption is supplied by coal-fired power plants. The remaining 80% is supplied by the technologies Obama categorized as clean: natural gas, coal with CCS, and carbon free (including nuclear fission and renewables). These are allocated to the mix based on the prioritization strategies outlined in the main paper. In 2050 we allocate 100% to clean technologies following the same strategies.

[1] If trends of slowly increasing electrification of energy continue (0.2% per year on average in terms of primary energy since 1990), this places a more stringent constraint on electricity than other energy demand sectors. Major electrification of transportation would justify an increase in the percent allocation of emissions to electricity. Depending on changes to secondary energy consumption, the carbon intensity target for electricity could increase, and the model presented can be adapted to reflect this. Note that there are arguments for placing more stringent constraints on electricity due to the availability of scalable, low-carbon supply technologies.

[2] The energy intensity in this context is the electricity intensity of total GDP. The extrapolated historical rate of change in electricity intensity of GDP includes a contribution from increasing electrification of energy.

[3] EPRI's estimate for economic savings potential is 473 TWh in 2020 compared to McKinsey's estimate for NPV-positive potential of 1080 TWh in the same year.

## 1.2 General Relationships and Sensitivity of Results to Model Assumptions

Here we discuss the sensitivity of the carbon intensity target to various assumptions, and the sensitivity of the portfolio allocations to a change in the carbon intensity target. By rearranging equation (1) we see that $c_t = C_t \frac{1}{E_t}$, and because of the product rule, the proportional change in the carbon intensity target $\Delta c_t / c_t$ due to changes in model assumptions is equal to the sum of the proportional change in the carbon emissions allocated and the proportional change in the reciprocal of the electricity consumption.

$$\frac{\Delta c_t}{c_t} = \frac{\Delta C_t}{C_t} + \frac{\Delta(\frac{1}{E_t})}{(\frac{1}{E_t})} \tag{2}$$

We have made an approximation here by disregarding the term $\frac{\Delta C_t \Delta(\frac{1}{E_t})}{C_t(\frac{1}{E_t})}$, which is only appropriate when the relative errors are small and we are interested in an answer with limited significant digits.

This relationship means that if the carbon emissions allocated to US electricity are 10% lower than expected and the electricity consumption is $11\%$ higher than expected, the carbon intensity target will be approximately 20% lower (more stringent) than expected. Error in the carbon intensity target in a given year ($c_t$) may arise for any of the following reasons:

- A different target value could be set for emissions in a given year. Emissions reductions could be shifted forward or backward in time. Relative reductions in emissions could be allocated differently across energy sectors. Cumulative emissions targets for the US could also change, which would affect annual targets.
- Electricity consumption in a given year, $E_t$, could be higher or lower. This could be due to a greater or lesser potential for decreased energy intensity ($e$). See footnote for the relationship between the assumed rate of decline in energy intensity and the electricity consumption[4]. A different trajectory for GDP would also change the electricity consumption.

The product rule can similarly be applied to relate error in meeting the carbon intensity and energy consumption targets to the error in carbon emissions, as discussed in the main paper. Error within each of the other energy sectors (transportation, direct heating) will propagate in a similar fashion. Error across sectors will combine additively, not multiplicatively.

Changes to the target for carbon intensity would affect the portfolio allocations in the following way. The carbon intensity target is met by allocating a fraction of the mix to coal (subscript $coal$ below), to low-carbon, fossil-based technologies (natural gas, or coal+CCS, or an equal allocation to natural gas and coal+CCS - all are denoted by subscript $n$ below), and to carbon-free technologies (subscript $cf$ below)[5].

$$c_t = f_{t,n} c_n + f_{t,coal} c_{coal} + f_{t,cf} c_{cf} \tag{3}$$

In 2035 the fraction of coal-fired electricity is held constant at 20%, and the carbon intensity of coal electricity ($c_{coal}$) is also constant. Let the product: $f_{t,coal} c_{coal} = m$, a constant, and note that

[4] If the assumed exponential rate of decline for $e = E/GDP$ is $b$, but the actual rate is $c$: the relationship between the assumed electricity intensity at any point in time $e(t)$ and the actual electricity intensity $e'(t)$ will be: $e'(t) = de(t)^{(\frac{c}{b})}$, where $d = a^{(1-\frac{c}{b})}$. This is because if $e(t) = ae^{-bt}$, and $e'(t) = ae^{-ct}$, then $\ln e(t) = \ln a - bt$ and $\ln e'(t) = \ln a - ct$, so that $\frac{(\ln e(t) - \ln a)}{b} = \frac{(\ln e'(t) - \ln a)}{c}$.

[5] Because we allocate portfolio weights based on the average carbon intensity for a class of technologies, the solution is not exact.

$c_{cf} = 0$.

If the carbon intensity target $c'_t$ is 20% higher than that estimated (due to any of the reasons listed above), how will $f_{t,n}$ change? If:

$$c'_t = 1.2c_t \tag{4}$$

and $c_n$ is constant, then:

$$f'_{t,n} = 1.2f_{t,n} + \frac{0.2m}{c_n} \tag{5}$$

where $f_{t,n} \leq 0.8$.

In 2035, $m = 0.067$ $tCO_2eq/GJ$. For natural gas, $c_n$ equals 0.123 $tCO_2eq/GJ$, for coal+CCS $c_n$ equals 0.065 $tCO_2eq/GJ$, and for an equal split between natural gas and coal+CCS $c_n$ equals $(c_{natgas} + c_{coalccs})/2 = 0.094$ $tCO_2eq/GJ$ [1, 2, 19, 20].

And in 2050, $m = 0$. Therefore, the proportional increase in carbon intensity will be equal to the increase in coal, natural gas, and coal+CCS and natural gas.

The carbon intensities we have assumed for natural gas, coal, and coal with CCS are mean values. Estimates for both coal and natural gas fired electricity are based on data, and we note that these values in the US have not followed increasing or decreasing trends in recent decades [1, 27, 17]. (We note that more stringent constraints may be placed on what is considered "clean natural gas". Equation 5 can be used to adapt portfolios based on a different value for carbon intensity.)

The carbon intensity estimate for coal + CCS is based on a projection and is considered relatively optimistic [19, 20]. (However, with incorporation of biomass this technology could be moved into the carbon free category [4, 3]. The scalability and therefore the ability to influence the mean value is under debate.) Renewables such as wind and solar, as well as nuclear fission, also emit small amounts of greenhouse gases, but as the average carbon intensity of the energy mix decreases, this number will approach zero. (Emissions arise in manufacturing, installation and maintenance, rather than direct emissions from fuel combustion as in the case of fossil fuels [27].) Including these emissions would not have a measurable effect on our results.

Here we demonstrate graphically the portfolios that would result from somewhat different assumptions. In Figure S1 we show portfolios consistent with a carbon intensity target that is 10% higher than the target shown in Figure 1 in the main paper, due to a 10% higher emissions allocation. For the high-efficiency scenario, as predicted by equation 5, the percent allocated to natural gas increases to 12% in 2035 for scenario 4. The percent CCS increases to 23% in scenario 5. And for scenario 6, natural gas and CCS increase to 8%.

The same 10% increase in the carbon intensity target (and the same portfolios) could arise from a (roughly) 10% lower electricity consumption. To achieve a 10% lower electricity consumption in 2035 than shown in the high-efficiency scenario, either the GDP or the E/GDP would have to be 10% lower in that year. The latter would be achieved by increasing the rate of decline in E/GDP for the years 2010-2030 to 2% rather than the 1.5% that was used in the original high-efficiency scenario, followed by a return to the baseline rate of decline of 0.9% between 2010 to 2035. Alternatively, using the analytical expressions in footnote 4, a rate of decline of 1.8% per year between 2010-2035 would result in 10% lower electricity consumption.

In Figure S2 we show portfolios consistent with a 10% lower carbon intensity target than in Figure 1 of the main paper, due to a 10% lower emissions allocation. In 2035, the target cannot be met under the low-efficiency scenario. Even with 80% carbon-free technologies, the emissions are 12% above the target. In 2035, the carbon intensity target is barely met in the high-efficiency scenario. Natural gas decreases to roughly 0.3% in scenario 4; CCS decreases to 0.6% in scenario 5; and in scenario 6, natural gas and CCS decrease to 0.4%.

# 2 Modeling the Retirement of Power Plants

## 2.1 Model

We use a vintage-based approach, as in previous studies, to model power plant retirement [8]. The Platts World Electric Power Plants Database, March 2010 database provides the age and fuel type of power plants across the world [24]. To predict generator retirement, we calculate the expected lifetime of a generator by averaging the lifetimes of previously retired generators, grouped by primary fuel source [24]. Generators with the same primary fuel source are assumed to have the same expected lifetime. For example, coal plants, natural gas plants, and solar PV plants had lifetimes of 39, 36, and 15 years, respectively, which is close to expected lifetimes calculated in previous works [8].

This method of predicting retirement makes the following simplifying assumptions. Firstly, generators from all sectors (utilities, commercial, industrial, independent power producers) are treated in the same way. In addition, we make no distinction between combined heat and power (CHP) and non-CHP facilities. Secondly, although a single power plant can have multiple generators, each generator is retired independently of the others in the same plant in this model. Thirdly, generators that were already operating past their expected lifetimes in 2010 are retired randomly over the next 5 years, a method used in previous studies [8]. This approach accelerates the rates of retirement in the first 5 years of the model, as seen in Figure 3C in the main paper. Lastly, it is important to note that the Platts database's data for China is relatively less accurate, due to problems such as underreporting. These issues are described further in the database's manual [24].

Next, we assign a retirement year to each generator in commercial operation or with standby or shutdown status. For each year after 2010, we calculate a "phase-out pattern" of the amount of nameplate generation capacity that has not yet been retired in that year [21]. We multiply the phase-out pattern of generation capacity by a fleet-wide-average capacity factor to create a phase-out pattern for total electricity generation, using 2010 as the base year to match data on net electricity generation from the International Energy Outlook [2].

An alternative to this deterministic approach would be to stochastically assign retirement years to each generator, based on the historic distribution of lifespans for that generator type. However, these historic distributions of lifespans are generally symmetric and bell-shaped, so we expect that a method that samples from stochastic lifespans would produce results similar to one using the expected value of the distribution. To quantify the uncertainty about the lifespans of power plants, we compare model runs that used longer and shorter lifespans than expected, as discussed further in section 2.3. This sensitivity analysis also captures the uncertainty and variation in capacity factors across the fleet of power plants.

## 2.2 Calculating Carbon Intensity of New Build under Carbon Constraints

Carbon intensities of plants with various fuel types are based on empirical data [27]. Fuel types that were not easily categorized are assigned an average carbon intensity in each country, such that the country-wide average carbon intensity of electricity accurately predicts that in the base year

(2010). Because the unlisted plants constitute under 10% of the total generation capacity, we expect this approximation to have a negligible effect on the results. By assigning a carbon intensity to each power plant and using the fleet-wide capacity factor described above, we estimate the annual $CO_2$-equivalent emissions that would be emitted from existing power plants in each year.

The carbon emissions reduction for Annex 1 countries in Scenario A are based on President Obama's goal for the US of 17% below 2005 levels by 2020 (equivalent to 12% below 1990 levels by 2020) [23]. To remain consistent with a 450 ppm stabilization target, the corresponding carbon emissions reduction for non-Annex 1 countries are estimated to be 28% below a business-as-usual case in 2020 [10]. The second carbon constraint scenario, Scenario B, also targets 450 ppm, with reductions of 35% below 1990 levels by 2020 for Annex 1 countries, and 15% below a business-as-usual scenario in 2020 for non-Annex 1 countries [10]. Scenario B represents a case of greater emphasis on emissions reductions in Annex 1 countries. We calculate a business-as-usual scenario for China and India by multiplying the EIA's IEO projections of electricity generation by our calculated average carbon intensity in 2010 [2]. Carbon emissions in 1990 are based on data provided by the World Bank [28].

The proportion of a region's carbon emissions cap allocated to electricity generation is the proportion of that region's historic emissions from electricity in 2010 compared to its economy-wide emissions. Given this assumption, all sectors would have to reduce emissions by the same proportion as the electricity sector in order for the region to reach their emissions reduction target.

The difference between the carbon emissions target and the carbon emitted from existing plants in that year represented the "headroom" of emissions reserved for newly constructed plants. From this, we calculate the required carbon intensity of new plants in order to meet the carbon constraint. These calculations are performed for both carbon constraint scenarios.

Table 1 compares the average carbon intensity of today's generators that remain in operation in 2020, the average carbon intensity of generators built between 2010 and 2020 required to meet the emissions reduction target in 2020, and the average carbon intensity of all generators in 2020 required to meet the emissions reduction target. In Scenario A, the carbon intensity of new build is slightly lower than the average carbon intensity target in Annex 1 countries, but is significantly lower in non-Annex 1 countries (China). In Scenario B, the carbon intensities of new build in all countries are significantly lower than both the average carbon intensity target and the carbon intensity of existing plants. Thus the infrastructural inertia in Annex 1 countries, from an emissions reduction perspective, is much larger for Scenario A.

## 2.3 Sensitivity Analysis of Power Plant Retirement Model

The timing of the retirement of a power plant depends on a number of variable factors, such as the economy and government regulations, and is therefore uncertain. We perform a sensitivity analysis to show the magnitude of variance in the results that is expected from this uncertainty.

We add or subtract 10 years from the expected lifespans of all generators to represent scenarios of high and low infrastructural inertia, respectively. The high infrastructural inertia case corresponds to a greater amount of future emissions from existing plants, while the low inertia case corresponds to lower future emissions. The projections for the US and Europe in general are more sensitive to changes in plant lifetimes in the short-term because these regions have a large number of older power plants that are predicted to be on the verge of retirement. Note that in the high inertia case under Scenario B, the future emissions from existing plants for the US and Europe exceed the emissions target in 2020. The results of the sensitivity analysis are shown in Figures S3, S4, S5, S6.

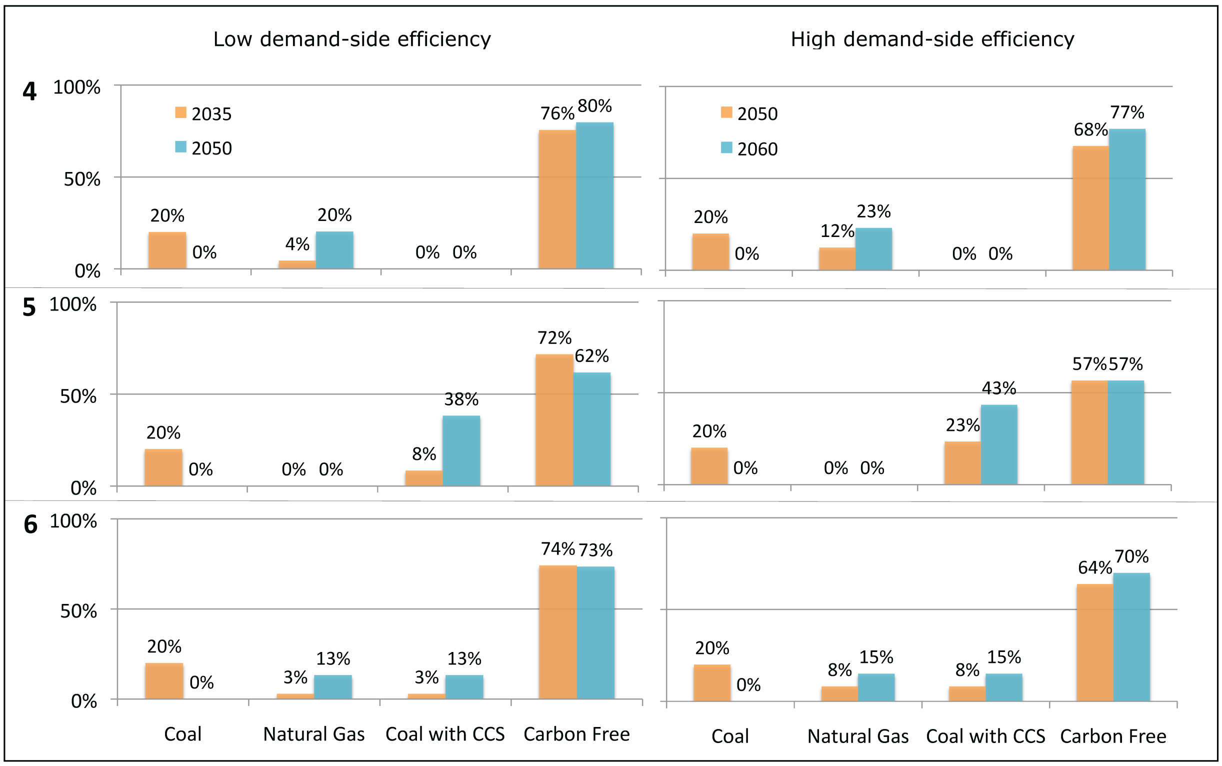


Figure 1: Technology portfolios that meet a 10% higher carbon intensity target due to a 10% increase in allocated carbon emissions in each year. Low-efficiency scenario (left); high-efficiency scenario (right). Portfolios include 20% coal generation in 2035 and 0% in 2050. (4) Natural gas with carbon-free generation added as necessary to meet the target. (5) Coal with CCS, and carbon-free generation added to meet the target. (6) Equal allocations to natural gas and coal with CCS, and carbon-free generation added as necessary.

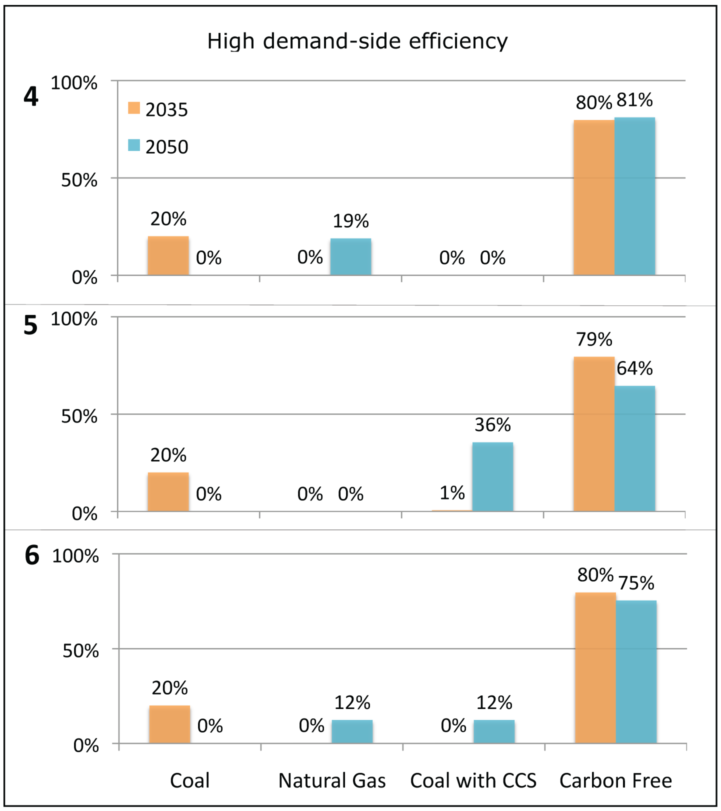


Figure 2: Technology portfolios that meet a 10% lower carbon intensity target. (The target may be lower because of a 10% decrease in allocated carbon emissions in each year.) We show the high-efficiency scenario; the target cannot be met in the low-efficiency scenario. Portfolios include 20% coal generation in 2035 and 0% in 2050. (4) Natural gas with carbon free generation added as necessary to meet the target. (5) Coal + CCS with carbon free generation added to meet the target. (6) Equal allocations to natural gas and coal with CCS, with carbon free generation added as necessary.

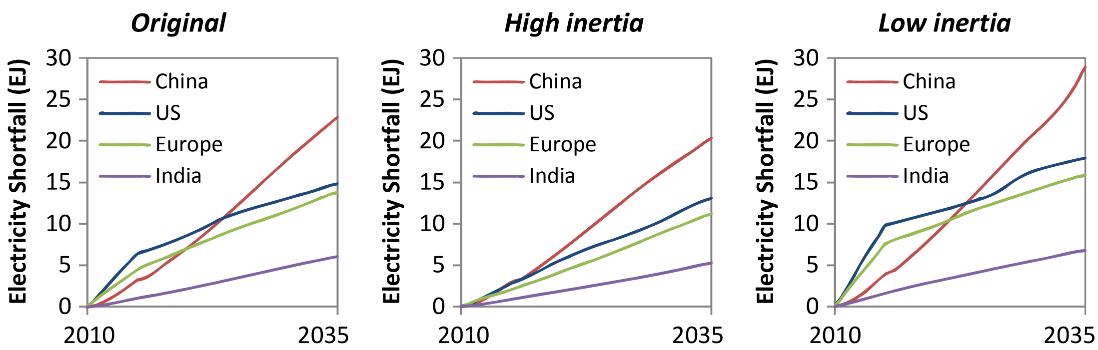


Figure 3: Electricity shortfall for regular, high, and low infrastructural inertia scenarios. Electricity shortfall is the difference between projected electricity demand and projected electricity supply from plants existing in 2010 as they are retired. Projections for the US and Europe are more sensitive to changes in plant lifetimes in the short-term because these regions have a large number of older power plants that are predicted to be on the verge of retirement.

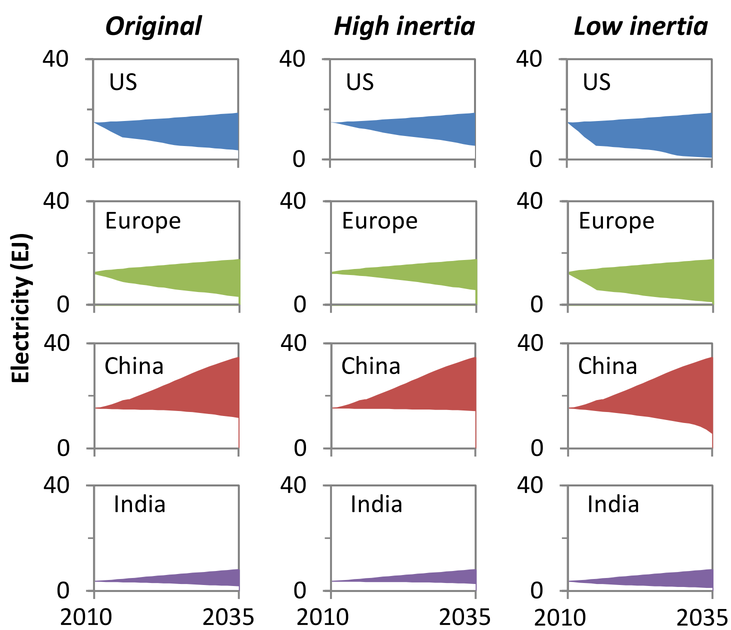


Figure 4: Shaded areas illustrate the nature of the electricity shortfall in regular, high, and low infrastructural inertia scenarios. The upper edge of the projected electricity demand, and the lower edge is the electricity supply from plants existing in 2010 as they are retired. Differences in plant lifetimes between the scenarios alter the slope of the electricity supply projection (lower edge).

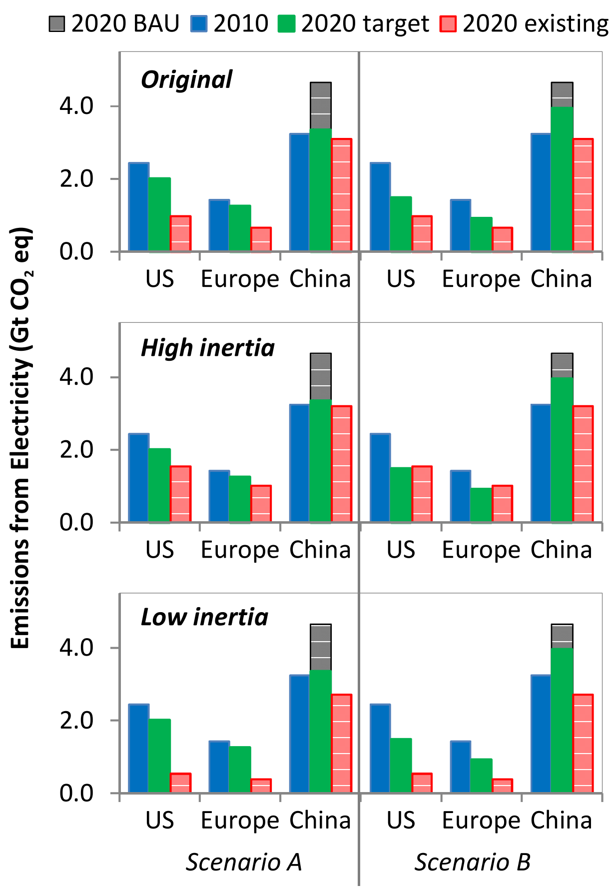


Figure 5: Comparison between countries of historic 2010 emissions, 2020 emission targets, emissions from today's plants that still exist in 2020, and emissions in 2020 for a business-as-usual scenario, in regular, high, and low infrastructural inertia scenarios. The different plant lifetimes in the regular, low, and high inertia scenarios are reflected in the amount of emissions from plants still existing in 2020 - higher inertia corresponds to higher "committed" emissions. Note that in the high inertia case, the emissions from existing infrastructure exceed the emissions targets for US and Europe in Scenario B. Scenario A targets stabilization at 450ppm, with Annex 1 countries reducing by 12% below 1990 levels by 2020 and others by 28% below a BAU scenario in 2020. Scenario B targets 450ppm, with Annex 1 countries reducing by 35% below 1990 levels by 2020 and others by 15% below a BAU scenario in 2020 [10].

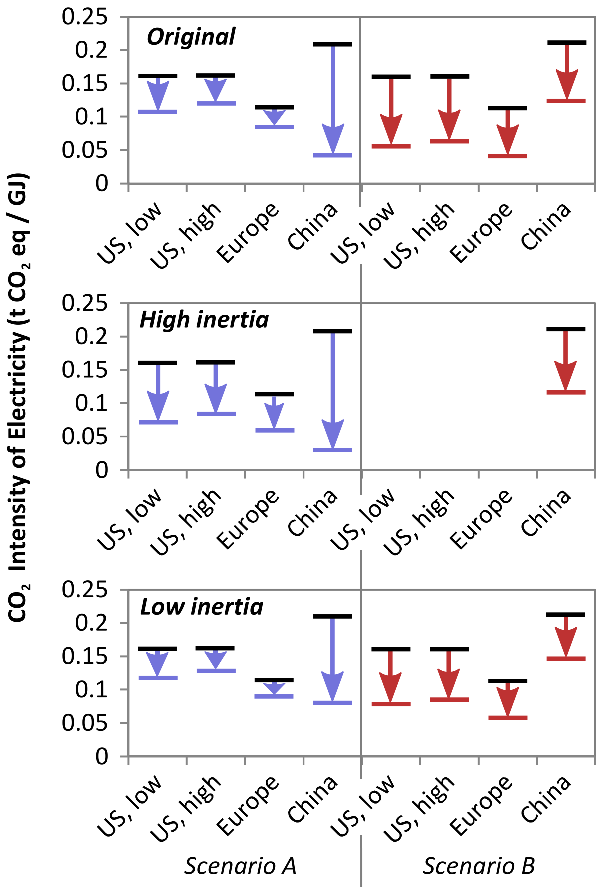


Figure 6: Carbon intensity of electricity in 2010 in various countries, and the carbon intensity of new electricity generation required to meet the 2020 emissions targets, in regular, high, and low infrastructural inertia scenarios. The top (dark) bar is the carbon intensity of electricity in 2010, and the lower (lighter) bar is the carbon intensity of new generation required to meet the 2020 emissions targets. Note that the results are not shown in the high inertia case for scenario B for the US and Europe, because the emissions from existing infrastructure exceed the target. Therefore the carbon intensity of new generation needed to meet the target would be negative. Scenario A targets stabilization at 450ppm, with Annex 1 countries reducing by 12% below 1990 levels and others by 28% below baseline. Scenario B targets 450ppm, with Annex 1 countries reducing by 35% below 1990 levels and others by 15% below baseline [10].

| | | US, low | US, high | Europe | China |
|---|---|---|---|---|---|
| | Existing plants | 0.132 | 0.132 | 0.089 | 0.212 |
| Scenario A | New build | 0.105 | 0.118 | 0.084 | 0.035 |
| | Average | 0.117 | 0.125 | 0.087 | 0.154 |
| Scenario B | New build | 0.052 | 0.058 | 0.037 | 0.119 |
| | Average | 0.086 | 0.092 | 0.064 | 0.182 |

Table 1: Carbon intensities in 2020 (t/GJ). This table compares the average carbon intensity of today's generators that have not been retired by 2020, the average carbon intensity required for new generators built between 2010 and 2020 to meet the emissions reduction target in 2020, and the average carbon intensity of all generators in 2020 required to meet the emissions reduction target. In Scenario A, the carbon intensity of new build is similar to the average carbon intensity target in Annex 1 countries, but is significantly lower in non-Annex 1 countries (China). In Scenario B, the carbon intensities of new build in all countries are significantly lower than both the average carbon intensity target and the carbon intensity of existing plants. Scenario A targets stabilization at 450ppm, with Annex 1 countries reducing by 12% and others by 28% below baseline. Scenario B targets 450ppm, with Annex 1 countries reducing by 35% and others by 15% below baseline [10].

# References


[1] Energy Information Administration. Annual energy review. 2008.

[2] Energy Information Administration. International energy outlook. 2009.

[3] C. Azar, K. Lindgren, M. Obersteiner, K. Riahi, D. P. van Vuuren, K. M. G. J. den Elzen, K. Mollersten, and E. D. Larson. The feasibility of low $CO_2$ concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change*, 100(1):195–202, 2010.

[4] M. Carpentieri, A. Corti, and L. Lombardi. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with $CO_2$ removal. *Energy Conversion and Management*, 46(11-12):1790 – 1808, 2005.

[5] J. Chandler. A preliminary look at electric efficiency potential. *The Electricity Journal*, 23:85–91, 2010.

[6] McKinsey & Company. EPRI and McKinsey Reports on Energy Efficiency : A Comparison. Technical report, 2009.

[7] McKinsey & Company. Unlocking Energy Efficiency in the U.S. Economy. Technical report, 2009.

[8] S. J. Davis, K. Caldeira, and H. D. Matthews. Future $CO_2$ Emissions and Climate Change from Existing Energy Infrastructure. *Science*, 329(5997):1330–1333, 2010.

[9] M. den Elzen and N. Höhne. Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. *Climatic Change*, 91(3-4):249–274, 2008. ISI Document Delivery No.: 372YQ Times Cited: 18 Cited Reference Count: 54 den Elzen, Michel Hohne, Niklas.

[10] M. den Elzen and Niklas Höhne. Sharing the reduction effort to limit global warming to 2°C. *Climate Policy*, 10(3):247–260, 2010.

[11] EIA. Electric power annual with data for 2009. Technical report, 2010.

[12] EPA. Trends in greenhouse gas emissions. Technical report, 2010.

[13] EPRI. Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S. (2010–2030). Technical report, 2009.

[14] Center for International Earth Science Information Network (CIESIN). Country-level Population and Downscaled Projections based on the B2 Scenario, 1990-2100. Technical report, 2002.

[15] S. Kaufman. G8 nations agree to cut carbon emissions by 80 percent by 2050. *America.gov*, 2009.

[16] Y. Kaya. Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios, 1990.

[17] J. McNerney, J. D. Farmer, and J. E. Trancik. Historical costs of coal-fired electricity and implications for the future. *Energy Policy*, 39:3042–3054, 2011.

[18] M. Meinshausen, N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen. Greenhouse-gas emission targets for limiting global warming to 2 degrees C. *Nature*, 458(7242):1158–1162, 2009.

[19] B. Metz, O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer. IPCC Special Report on Carbon Capture and Storage. Technical report, 2005.

[20] MIT. The future of coal. Technical report, Massachusetts Institute of Technology, 2007.

[21] M. Odenberger and F. Johnsson. Achieving 60% $CO_2$ reductions within the UK energy system - Implications for the electricity generation sector. *Energy Policy*, 35(4):2433–2452, April 2007.

[22] US Department of Commerce. National economic accounts. Technical report, 2010.

[23] Office of the Press Secretary. President to Attend Copenhagen Climate Talks. *Whitehouse.gov*, 2009.

[24] Platts. World Electric Power Plants Database, March 2010. Technical report, 2010.

[25] I. Rohmund, G. Wikler, A. Faruqui, O. Siddiqui, and R. Tempchin. Assessment of Achievable Potential for Energy Efficiency and Demand Response in the U.S. (2010 – 2030). In *2008 ACEEE Summer Study on Energy Efficiency in Buildings 5-261*, volume 2030, pages 261–272.

[26] Core Writing Team. *Synthesis Report: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, 2007.

[27] D. Weisser. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy*, 32(9):1543–1559, 2007.

[28] World Bank. World Development Indicators (WDI) online databank, 2012.