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Effectiveness of a Segmental Approach to Climate Policy

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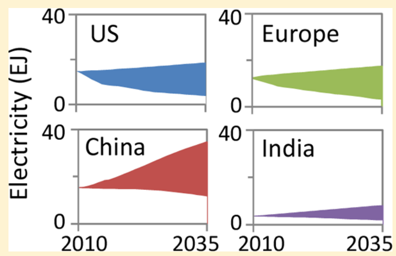
Supporting Information

ABSTRACT: Resistance to adopting a cap on greenhouse gas emissions internationally, and across various national contexts, has encouraged alternative climate change mitigation proposals. These proposals include separately targeting clean energy uptake and demand-side efficiency in individual end-use sectors, an approach to climate change mitigation which we characterize as segmental and technology-centered. A debate has ensued on the detailed implementation of these policies in particular national contexts, but less attention has been paid to the general factors determining the effectiveness of a segmental approach to emissions reduction. We address this topic by probing the interdependencies of segmental policies and their collective ability to control emissions. First, we show for the case of U.S. electricity how the set of suitable energy technologies depends on demand-side efficiency, and changes with the stringency of climate targets. Under a high-efficiency scenario, carbon-free technologies must supply 60−80% of U.S. electricity demand to meet an emissions reduction target of 80% below 1990 levels by midcentury. Second, we quantify the enhanced propensity to exceed any intended emissions target with this approach, even if goals are set on both the supply and demand side, due to the multiplicative accumulation of emissions error. For example, a 10% error in complying with separate policies on the demand and supply side would combine to result in a 20% error in emissions. Third, we discuss why despite these risks, the enhanced planning capability of a segmental approach may help counteract growing infrastructural inertia. The emissions reduction impediment due to infrastructural inertia is significant in the electricity sectors of each of the greatest emitters: China, the U.S., and Europe. Commonly cited climate targets are still within reach but, as we show, would require more than a 50% reduction in the carbon intensity of new power plants built in these regions over the next decade.



INTRODUCTION

Placing a constraint on yearly emissions flux, or cumulative emissions,[1] is a widely recognized approach to climate change mitigation, and cap and trade is thought by many to be a logical and economically efficient policy instrument to enforce this constraint.[2,3] A key feature of a cap and trade mechanism is that it allows the market to distribute emissions reductions across end-use sectors, and across demand-side efficiency and supply-side technology changes.[4] But political and public resistance to cap and trade have encouraged several other policy proposals.[5,6]

Clean energy standards complemented by demand-side efficiency regulations have emerged as a possible alternative to direct carbon control. We characterize these policies as *segmental* because they separately target changes on the supply-side and demand side in individual end-use sectors (e.g., electricity, transportation), rather than directly addressing emissions through a sectoral or economy-wide emissions cap.

Several nations have policies that can be classified as segmental (Table 1). In China, for example, the national government has focused on energy intensity targets on the demand side since 2006, as well as supply-side improvements in coal plant efficiency and renewable energy deployment.[7] The United States is considering a clean energy standard that would target supply-side transformations in power generation.[8,9] Given that China and the United States together represent roughly 40% of worldwide carbon dioxide emissions,[10] the performance of segmental policies in these two countries alone will have a major impact on global emissions and the climate response.

As several papers have argued, this segmental, technology-centered approach may prove less economically efficient than a carbon cap or tax[2,11,12] under assumptions of a high degree of foresight and coordination in the market. Market foresight would result in a least-cost allocation of emissions reduction across future decades (including, for example, the adoption of new supply technologies rather than a more short-sighted focus on demand-side efficiency alone), and coordination would result in an efficient allocation by the market of emissions reduction across different actors. When these assumptions are relaxed, however, studies suggest that technology-specific policies could be more efficient in stimulating the technological development required for long-term mitigation.[12−14] Here we acknowledge this debate on economic efficiency and focus instead on evaluating a segmental policy approach from the

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Table 1. Segmental and Integrated Policies

region	supply-side policies	demand-side policies	integrated policies
China	Target: 15% of electricity from renewables by 2020; 15 GW solar and 70 GW wind by 2015 (passed). Policy framework: Five- Year Plan; Feed-in tariffs (passed).[37]	Target: Reduce energy intensity by 16% from 2010 levels by 2015 (passed). Policy framework: Five- Year Plan; National energy cap (discussed).[37]	Target: 17% reduction in carbon intensity of GDP by 2015; 40−45% reduction in carbon intensity of GDP from 2005 levels by 2020 (passed).[7]
European Union	Target: 20% of electricity to come from renewable resources by 2020 (passed).[38]	Target: 20% below baseline projections for 2020 (proposed)[39]	Target: 20% reduction of GHGs below 1990 levels by 2020 (passed).[40]
India	Target: 20 GW of solar capacity by 2022. Policy framework: National Solar Mission (passed).[41]	Target: 10 GW below baseline projections by 2012. Policy framework: National Mission for Enhanced Energy Efficiency (passed).[42]	Policy framework: National Action Plan on Climate Change (passed).[42]
United States	Target: Clean Energy Standard to meet 80% of electricity demand with clean energy by 2035 (proposed).[8,15,16]	Policy Framework: No national policy, but Energy Efficiency Resource Standards exist in 23 states (passed).[43]	Target: 17% reduction in greenhouse gas emissions below 2005 levels by 2020 (proposed).[44]

perspective of its potential effectiveness in controlling emissions.

Using the example of the proposed U.S. Clean Energy Standard for electricity,[15−18] we show how an emissions target might be met with a coordinated set of segmental policies. We show how the set of suitable energy technologies[19] changes with the stringency of climate targets and the extent of demand-side efficiency measures. Regardless of the climate target adopted, our analysis demonstrates an enhanced risk that emissions will substantially exceed intended levels with segmental policies, even if coupled goals are set on the demand and supply side. This results from properties of the identity relating carbon intensity, energy consumption and emissions. Conversely, a potential benefit of the segmental approach is an ability to deal with infrastructural inertia[20] through direct government regulation mandating the adoption of low-carbon energy supply technologies. We show that infrastructural inertia is significant in China, the U.S., and Europe, the largest emitters.

The demand and supply-side relationships, and other general features of a technology-centered, segmental approach to emissions control that we identify in studying the electricity sector are relevant across national contexts, other end-use sectors,[21−23] and a spectrum of stringency in climate targets. These features are important to understand in the near-term, to inform the debate on detailed plans for policy implementation.[8]

■ MATERIALS AND METHODS

Probing the Interdependency of Supply and Demand-Side Changes to Meet Climate Targets. To understand the conditions that allow a segmental policy approach to remain consistent with emissions targets, we used the United States' proposal for an electricity sector clean energy standard as a case study. The objective was to study how the carbon intensity reductions and the set of possible technologies to meet these reductions depend on the climate target stringency and demand-side efficiency. The general relationships identified are relevant across end-use sectors and countries with increasingly segmental climate policies.

We decomposed carbon dioxide equivalent emissions from electricity at each point in time:[24]

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

where emissions (C_t) are the product of GDP_t, electricity intensity of the economy ($e_t = E_t/GDP_t$) and the carbon intensity of electricity ($c_t = C_t/E_t$) with E_t representing electricity consumption. The emissions control variables are electricity intensity on the demand side (secondary energy at the busbar per unit GDP), and carbon intensity on the supply side (carbon dioxide equivalent emissions per unit secondary energy). We derived a carbon intensity target in each year that depends on the allowable greenhouse gas emissions from electricity, divided by the electricity consumption.[24,25]

The U.S. emissions trajectory studied reduces emissions to 80% below 1990 levels by 2050 (83% below 2005 levels by 2050) and meets the shorter term emissions reduction goals the U.S. outlined prior to the United Nations Climate Change Conference in Copenhagen: 17% below 2005 levels by 2020, 30% below 2005 by 2025, and 42% below 2005 by 2030 (Figure 1).[26] The U.S. goal to reduce emissions 80% by 2050 was set in accordance with limiting global warming to 2 °C,[1,27,28] although it 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_2eq.[29−31] This stabilization

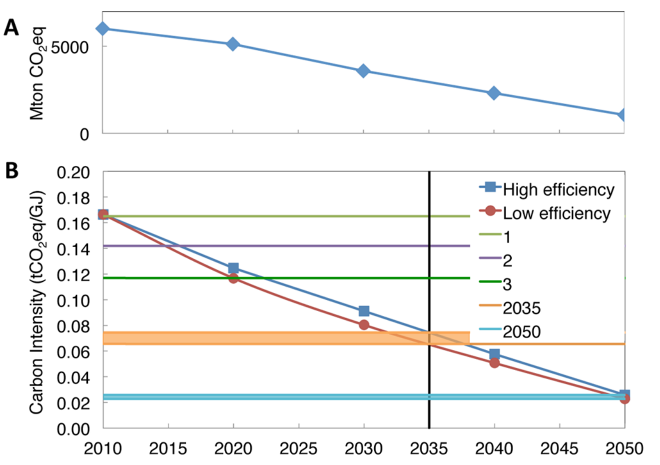

Figure 1. (A) Emissions trajectory reaching 80% below 1990 levels by 2050. (B) Carbon intensity targets consistent with the emissions trajectory under low (baseline) and high demand-side efficiency. Carbon intensities for three energy portfolios that meet the clean energy standard but exceed the emissions constraint: (1) In light green, 20% coal and 80% natural gas fired electricity. (2) In purple, 20% coal, 40% natural gas, and 40% coal with CCS. (3) In dark green, 20% coal, 27% natural gas, 27% coal with CCS, and 27% carbon free (nuclear, renewables).

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level was consistent with a less than 2 °C global mean temperature increase in roughly 50% of the models assembled by the Intergovernmental Panel on Climate Change.[32,33] A fraction of emissions was allocated to the electricity sector based on today's electricity emissions relative to those from other end-use sectors, and the allowable emissions (C_t) were constrained to meet the reduction targets noted above. Meeting the overall emissions constraint in this model would require an equal percent reduction in emissions across all sectors, but this assumption can be varied to study other end-use sector emissions allocations (see Results section and the Supporting Information (SI)).

High and low demand-side efficiency scenarios were based on a meta-analysis of electricity efficiency potential in the U.S.[9,34,35] Two trajectories were developed for the energy intensity (e_t) based on high and low demand-side efficiency scenarios.

Given the emissions allocations in each year, a baseline projection for GDP, and two trajectories for energy intensity, the carbon intensity targets (c_t) were then calculated. Technologies were selected to meet the carbon intensity targets based on their carbon intensities and using technology prioritization strategies, as outlined in detail in the results section.

The SI includes analytical expressions to investigate any efficiency assumption or emissions allocation, and the resulting impact on the carbon intensity target and technology portfolios. These expressions were also used to estimate the accumulation of emissions error with a segmental policy approach.

Measuring the Emissions Reduction Impediment Due to Infrastructural Inertia. To understand the potential benefits of controlling infrastructural changes through a segmental approach, we investigated the degree of infrastructural inertia in the largest emitters (SI). We focused on the U.S., EU, China, and India and the degree of committed infrastructure based on a global power plant database.[36] We developed several metrics to assess the impediment infrastructural inertia poses to emissions reduction. The metrics included the committed infrastructure, in units of capacity, the expected future energy generation from these power plants, and the difference between the expected energy consumption and generation from committed plants.

The analysis involved developing a model to estimate retirement of existing power plants based on their age and expected lifetimes. We also determined the expected replacement rate for power plants by comparing existing plants to the projected growth in electricity consumption. We then determined the carbon intensity required for those new power plants under a baseline electricity consumption projection and a carbon cap allocation in the years 2020 and 2035. Sensitivity analyses were performed to test the dependence of the results on model input assumptions. Several carbon allocations for Annex I and non-Annex I countries were considered.[29,30] A different baseline electricity consumption projection was considered for each country. Further details on the methods used are given in the SI, section 2.2.

■ RESULTS

We begin by investigating how a coordinated set of segmental policies could be used to meet emissions targets for the case of U.S. electricity. We then discuss factors determining emissions error accumulation from segmental policies in electricity and other end-use sectors. Finally, we quantify infrastructural inertia in the largest emitters, China, the U.S., and Europe, and highlight the potential role for supply-side segmental policies to address this issue.

Technology Portfolios' Dependence on Energy Efficiency—Exploring the U.S. Clean Energy Standard. Here we determine the technology portfolios and demand-side efficiency that would satisfy both the United States'clean energy standard proposal to meet 80% of U.S. electricity demand with clean technologies by 2035[15−18] and earlier commitments to reduce emissions 80% by 2050.[26]

A logical way to categorize technologies, if climate change mitigation is a motivating objective, is based on the technology's carbon intensity (SI).[19,45] The U.S. proposal included nuclear, coal with carbon capture, natural gas, wind, and solar in the list of clean technologies. To achieve the emissions reductions outlined, the portfolio weights assigned to each of these technologies need to be carefully specified (Figures 1 and 2). Focusing primarily on two technologies,

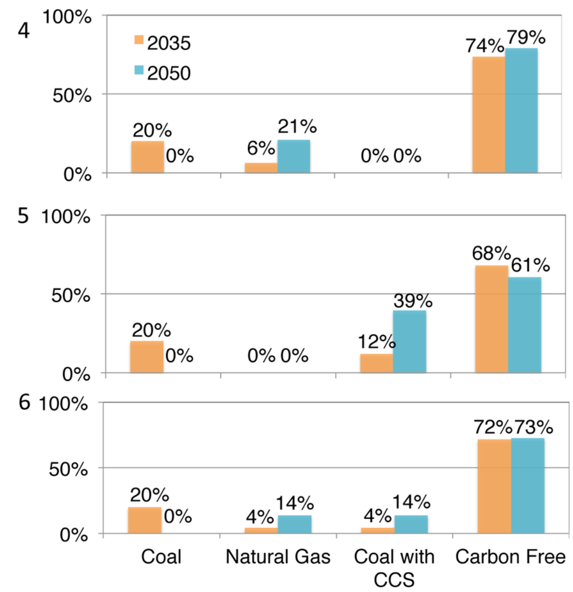

Figure 2. Technology portfolios in 2035 and 2050 to meet U.S. carbon intensity targets for a high demand-side efficiency scenario. Portfolios incorporate 20% coal generation in 2035 and 0% in 2050. Strategies shown are continued from Figure 1: (4) Natural gas with carbon-free generation (nuclear and renewables) added as necessary to meet the carbon intensity target. (5) Coal with CCS, and carbon-free generation added as necessary. (6) Equal allocations to natural gas and coal with CCS, and carbon-free added as necessary.

natural gas and coal, with carbon capture and storage (CCS), would put the U.S. far off its carbon intensity target, even in 2035 (Figure 1). Similarly, if the clean energy portfolio were split equally between natural gas, coal with CCS, and carbon-free technologies (such as wind, solar, and nuclear), the carbon intensity target would be missed.

How much carbon-free generation is required to meet these targets? Here we outline three representative strategies for providing 80% of electricity in 2035 in the United States from clean energy sources while adhering to emissions constraints (Figure 2). These strategies are (1) A focus on natural gas technologies; (2) A push for coal with CCS, and (3) An equal emphasis on natural gas and coal with CCS. In all three cases the allocation to fossil fuel based technologies included in the category of clean energy (natural gas, and coal with CCS) is

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maximized, and then supplemented by carbon-free technologies as necessary to stay on the specified emissions path. In 2035, 20% of electricity generation is allocated to coal, as implied in the 80% Clean Energy Standard.[15,16]

These strategies are applied again in 2050, when we assume that all electricity demand is met by the set of clean technologies proposed for inclusion in the standard;[15] coal is excluded. (Using more than 7% of coal without CCS would exceed the emissions target.)

Technology portfolios that meet the clean energy standard and the carbon intensity target, satisfying emissions constraints, reveal several notable points (Figure 2). Demand-side efficiency plays a key role, modulating the technology portfolios and providing additional time to meet a given carbon intensity target. In addition:

- Under baseline efficiency improvements, the U.S. cannot meet the emissions constraint in 2035. Emissions will exceed the target by several percent even if the clean energy standard is met entirely with carbon-free technologies. Note that the baseline trajectory already assumes a significant decrease in the energy intensity of the economy. This result highlights the important role for energy efficiency, though we note the anticipated challenges.[46,47]
- If efficiency improvements are more significant, at 1.5 times the historical rate to 2030 and then resuming the baseline rate (SI), the emissions constraint can be met in 2035, but only if carbon-free technologies predominate. Limited natural gas and coal with CCS can be used, supplying 6% and 12% of electricity respectively. (We note the debate on life-cycle carbon intensities of natural gas[48,49] and show in the SI how changing assumptions about the carbon intensities of technologies would affect portfolio allocations.)
- Because natural gas has roughly double the carbon intensity of coal with CCS (using the 100-year global warming potential), adding one unit of natural gas requires removing two units of coal with CCS from the technology portfolio. Furthermore, these low-carbon fossil fuels depend on energy efficiency for deployment in an emissions-constrained scenario.
- The U.S. clean energy standard as originally worded implicitly favors coal over natural gas under this emissions scenario because it allows for 20% coal generation by 2035. As a result, if emissions targets are met, coal far exceeds natural gas in electricity supply (see Figure 2). This feature could be changed by increasing the target for the clean energy standard to greater than 80%. If natural gas is deemed an important portfolio element, increasing the clean energy standard to greater than 80% clean energy, as defined above, may be preferable. More generally, this observation supports adopting a carbon intensity standard rather than a clean energy standard.[8,45]

Technology portfolios that meet the carbon intensity target in 2050 can be evaluated in light of the 2035 portfolios. The degree of continuity in portfolios depends on the strategy chosen. For example, prioritizing natural gas results in an initial decline in natural gas from today's levels to 2035 and subsequent growth by 2050 (Figure 2). This technological change trajectory is suboptimal given energy infrastructure's operating lifetimes, and the benefits of workforce continuity. This result suggests again that in the U.S. case a more ambitious clean energy standard, relying on less coal in 2035, may be preferable for meeting these emissions targets. More broadly, long-term infrastructure planning should include medium-term targets that are both consistent with climate goals and create stable infrastructure trajectories.[50]

Carbon-free technologies must supply 60–80% of electricity demand by 2050, under a high-efficiency scenario, to meet the emissions reduction target of 80% below 1990 levels by 2050. Natural gas and coal with CCS can supply the remainder (Figure 2). A review of historical technology growth rates provides additional perspective. Based on the current level of carbon free power generation in the U.S. and projected electricity output in 2050, the annual growth rate for carbon free technologies (excluding hydroelectricity which shows limited growth potential in the U.S.) should be in the range of 2.5–3.5% from 2010 to 2050 to meet the carbon intensity target explained above under high demand efficiency scenarios, and 3–4% under low demand efficiency. These implied growth rates fall within the range observed in recent decades. From 1990 to 2010, carbon free technologies (nuclear fission and renewables) in the U.S. grew at an average rate of 2.5% while renewables alone grew 7.5% per annum.[51]

These results outline constraints in the United States' electricity case examined, where technology portfolios must consist primarily of carbon-free generation to meet the 80% emissions reduction target alongside the clean energy standard. In addition, to meet the electricity sector emissions target, coupled constraints need to be set for supply-side technologies and demand-side efficiency. High demand-side efficiency and limits on natural gas are needed. Technology portfolios would be further specified, including the mix of carbon free-technologies, through market-based cost optimization,[50,52] if a credit trading scheme was implemented based on carbon intensity.[45]

These findings illuminate general interactions between supply and demand-side policies that are applicable to other end-use sectors and national contexts. (To meet a national or global emissions target, policies would need to target all greenhouse gas emitting end-use sectors. Segmental policies, as we have defined them, would address the supply and demand side of each sector separately.) The results highlight the importance of considering the supply and demand-side interactions during long-term planning for climate change mitigation. These relationships are further explored in the next section.

General Relationships between Climate Goals, Energy Efficiency, Carbon Intensity Targets, and Technology Portfolios. Carbon intensity targets are sensitive to assumptions about the electricity demand trajectory, and the emissions allocated to electricity. Technology portfolios are, in turn, sensitive to the carbon intensity targets. Developing a simple, transparent model for the United States electricity sector allows us to describe these relationships with analytical expressions, which can then be used to investigate other end-use sectors and a wide range of scenarios and national contexts (SI). (More detailed models highlighting endogenous relationships, such as the within-sector and cross-sectoral responses of demand to changes in the price signal, can complement this analysis.[33,53–55]) A simplified model can be effective at showing how model predictions depend on assumptions. Understanding these relationships is critical to stimulating an informed debate among scholars, policy makers and the public on the implications of segmental climate policies.

Following Eq. (1), the proportional change in the carbon intensity target in a given year ($\Delta c_t/c_t$) is equal to the sum of the proportional change in the carbon emissions allocated to electricity and the proportional change in the reciprocal of the electricity consumption:

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

(This is an approximation, disregarding the term:

$$\frac{\Delta C_t \Delta(1/E_t)}{C_t(1/E_t)},$$

which is appropriate when the relative changes are small and we are interested in an answer with limited significant digits.) If, for example, the carbon emissions allocated to U.S. electricity are 10% lower than assumed and the electricity consumption is roughly 10% higher, the carbon intensity target will be approximately 20% lower, creating a more stringent target.

Adjustments to the carbon intensity target in a given year (c_t) may arise for any of the following reasons:

- Electricity consumption in a given year, E_t, could be higher or lower due to a greater or lesser energy intensity (e_t). A divergence from the expected trajectory for GDP would also change the electricity consumption.
- A lower or higher emissions target could be set in any given year, meaning that emissions reductions would be shifted forward or backward in time. Relative reductions in emissions could be allocated differently across energy end-use sectors. Cumulative emissions targets for the U.S. could also change, which would affect annual targets.

The resulting technology portfolios are sensitive to a change in the carbon intensity target, particularly in the year 2035 in the U.S. case investigated above because in that year the amount of coal is fixed at 20%. Therefore the change in mean carbon intensity must come entirely from technologies other than coal (SI). In 2050 we assume no coal, and therefore the portfolios are less sensitive; the proportional change in natural gas or coal with CCS in the technology portfolios equals the proportional change in carbon intensity.

These general relationships emphasize the need for coordination among segmental policies, in order to meet emissions reduction targets. However, perfect coordination in setting demand and supply-side targets is unlikely. Furthermore, the risk of emissions error due to imperfect policy compliance is significant, as discussed in the next section.

Emissions Error Propagation Across Segmental Policies. The above expressions can similarly be applied to relate error in meeting the intended carbon intensity and energy consumption targets to the resulting error in carbon emissions. Even with carefully tailored demand and supply-side policy goals, there is considerable risk of missing emissions targets. Policy instruments only achieve their goals to within some degree of compliance error. Emissions are the product of carbon intensity and energy consumption, and therefore the proportional error in emissions is the sum of the proportional error in consumption and carbon intensity to carbon emissions. Because of error propagation through the equation relating electricity consumption and supply-side carbon intensity to carbon emissions, missing supply and demand-side targets by a modest amount can result in significantly higher emissions. Furthermore, given the difficulty in controlling energy demand, we note that we expect a large compliance error in meeting demand-side targets.

Comparing segmental policies to an emissions cap demonstrates this enhanced risk. A set of policy instruments that meets an intended emissions cap to within a 10% error would have at most 10% greater cumulative emissions than expected. Segmental policies that meet energy consumption and carbon intensity targets to within 10% error would result in a maximum of 20% higher cumulative emissions than intended. Similarly a 20% error on both the supply and demand side would result in 40% emissions error. In other words, error combines multiplicatively when separate policies target the supply side and the demand side, as is the case for segmental policies. In contrast, error across countries and end-use sectors combines additively rather than multiplicatively. Given that roughly 60% of global carbon dioxide emissions come from China, the U.S., Europe, and India, a 20% error resulting from segmental policies in these regions alone would translate to a 16% error in global emissions, with significant implications for warming. (This example is based on additive error across countries and sectors and multiplicative error across the demand and supply side.)

The potential for increased error poses a threat of substantially greater climate impacts than intended. At the global scale, a crude approximation shows that a 20% positive error on both the demand and supply side in meeting a 450 ppm CO_2eq stabilization target could result in a 2−4.5 °C global mean temperature rise, rather than the targetted 1.5−3 °C.[1,32,56] (This assumes that half of the global emissions allowance has been used and is known with certainty, and therefore meeting the remaining half of the emissions allowance with a 40% error results in a cumulative emissions error of 20%.)

The risk of rapidly accumulating errors is present regardless of the intended climate target. With less stringent climate targets, the same percent error noted above is associated with a higher temperature increase. If we consider the nonlinear relationships between temperature and the distributed impacts of climate change, the risk becomes even more severe.[57] If climate change mitigation is an objective of segmental policies, this potential for rapidly accumulating error and negative climatic outcomes points to the need for policy instruments that actively monitor the fidelity with which policy goals are met.

Compliance error is not the only source of error in meeting global climate targets. Decisions regarding emissions allocations over time and space are inherently difficult and unlikely to result in precise emissions control. For example, while policy makers may favor the simplicity of setting emissions reduction targets by a given year, the major determinant of climate change is the integral of emissions over time.[1,56] Allocations across countries are notoriously fraught due to equity concerns.[29−31] Furthermore, allocations across end-use sectors within countries, as required for sector-specific policies, are similarly difficult and contentious.

If policies do not address all nations and end-use sectors, global emissions control will necessarily be imprecise. Policies applied to only one sector or country could result in higher demand for greenhouse-gas emitting energy in other countries or end-use sectors because of the sensitivity of price to supply and the reaction of demand to price. However, the multiplicative compliance error associated with segmental policies that is discussed above (as compared to sectoral or economy-wide policies that directly limit emissions) will magnify the error due to these other reasons.

Planning to Counteract Infrastructural Inertia. While we have highlighted important concerns about segmental climate policies, there are also potential benefits due to the enhanced control over the significant infrastructural changes required to meet a climate target. Supply-side-specific segmental policies may help limit infrastructural inertia, which accumulates due to the long lifetimes of power plants. This inertia reduces the flexibility of the supply-side fleet to external changes such as emissions control.

Major emitters, including the EU, the U.S., and China, have already accumulated substantial infrastructural inertia in electricity generation. We explore this issue here by defining four metrics: the age distribution of the current infrastructure (Figure 3A); the difference between projected energy demand

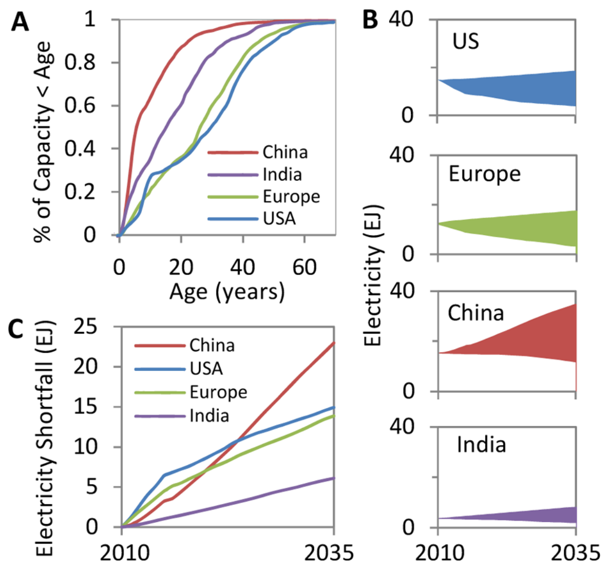

Figure 3. (A) Fraction of electricity generation capacity younger than a certain age. (B) Shaded areas show the projected shortfall in electricity generation: the upper edge is the projected electricity demand, the lower edge is electricity from plants existing in 2010 as they are retired. (C) Magnitudes of the shortfalls in each country are directly compared.

and projected energy supply from existing infrastructure (Figure 3B,C); committed emissions due to existing infra-structure relative to emissions caps (Figure 4A); and the carbon intensity of the new-build generation required to meet climate targets (Figure 4B).

Each nation's rank in infrastructural inertia changes with the metric applied. China has the largest percentage of young plants, but also a high projected energy consumption. The shortfall in energy generation, to be met by new plants, is greatest in China, followed by the U.S. and Europe, and then India. In terms of committed emissions relative to allowed emissions, the ranking is sensitive to the emissions targets assumed.[29,30] Depending on the stringency of emissions caps applied to Annex I and Annex II nations, the rank order of the U.S. and Europe versus China—in terms of allowed minus committed emissions in 2020—changes (Figure 4). For all nations and emissions caps considered, the required carbon intensity of new-build plants is even lower (in many cases much

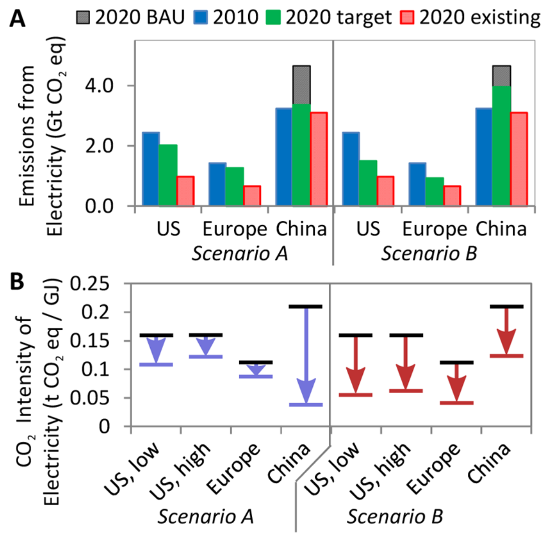

Figure 4. (A) Comparison of countries' historic 2010 emissions, 2020 emissions target, emissions from today's plants in 2020 after retirements, and emissions in 2020 for a business as usual (BAU) scenario. Scenario A targets stabilization at 450 ppm CO_2eq, with Annex 1 countries reducing by 12% below 1990 levels (17% below 2005 levels, the same goal as shown in Figure 1) and others by 28% below baseline.[29,30] Scenario B targets 450 ppm, with Annex 1 countries reducing by 35% below 1990 levels and others by 48% below baseline. (B) Comparison of carbon intensities of current (2010) electricity generation (top bar) and the carbon intensity required for new build (bottom bar) to meet the 2020 emissions targets noted above. For Scenario A, the required carbon intensity of new build in the U.S. (both high and low demand-side efficiency, labeled U.S., high and U.S., low respectively) and Europe is slightly lower than the fleet-wide target. (Fleet-wide includes all new and existing infrastructure. The fleet-wide carbon intensity targets are shown in Figure 1.) The required carbon intensity of new build is significantly lower than the fleet-wide target in China. For Scenario B, the carbon intensities of new build are significantly lower than both the fleet-wide carbon intensity target and the carbon intensity of existing plants (SI) in China, the U.S., and Europe.

lower) than that of the fleet-wide carbon intensity target (shown in Figure 1B for the U.S.), because of infrastructural inertia. These results highlight the immediate need to counteract growing infrastructural inertia, and to adopt significant carbon-free power in the next decade, if these climate targets are to be met.

Inertia can also accumulate on the demand side, due to the 10–20 year lifetimes of appliances such as refrigerators and washing machines, and a segmental approach can address this challenge as well. Indeed, a segmental approach offers greater control over the coordination of changes to the demand and supply side. For example, front loading low-cost demand-side efficiency improvements would maximize carbon savings in a scenario where the carbon intensity of the electricity supply decreases over time. An avoided unit of energy will achieve a greater emissions savings the earlier it is realized.

The greater certainty for investment and planning afforded by a segmental policy approach may help in training the workforce necessary to enable these large energy system transformations. From an engineering perspective, greater planning may help achieve a reliable, cost-effective integration of a new set of energy supply technologies into the electricity distribution and transmission system.

Planning may also influence how climate policy is perceived by policy makers and the general public. A segmental approach would show more clearly who the beneficiaries of a policy are, which may help garner support.[12] From a societal perspective, the ability to visualize the future energy infrastructure with greater certainty may lead to greater acceptance and therefore increased policy effectiveness.[58−62]

■ DISCUSSION

Climate policy discussions in the U.S., China, and several other major emitting countries are moving away from a global emissions cap toward more fragmented approaches. Although the specifics of many policies remain unresolved, there is a shift toward setting technology and demand-side efficiency goals that separately target the supply and demand side within individual end-use sectors at the national level. We call these efforts *segmental policies*. These policies are expected to differ in their performance from emissions caps applied globally, nationally or sectorally.

Under certain, idealized circumstances, this new approach can reduce emissions to the same degree as an emissions cap. This can only occur, however, under a stringent set of constraints on both the supply and demand side, and coordinated targets across end-use sectors (electricity, transportation, and heating). We show how supply and demand-side changes can work together to meet climate targets, through a simple model applied to the case of U.S. electricity. The results demonstrate the role of demand-side efficiency in buying some time for major decarbonization on the supply side, to meet commonly cited emissions reduction goals.

Moreover, even if targets are set for supply-side technology portfolios and for energy demand, emissions reduction goals may still be missed by a substantial margin. This result is due to two factors: policy instruments will only meet their targets imperfectly, and error will combine multiplicatively when meeting demand and supply-side targets separately. Demand-side targets may be particularly difficult to meet, as policies do not typically directly control energy consumption but rather address the energy intensity of economic activity. Furthermore, if policies are not applied to all end-use sectors, a changing demand in one sector could lead to a price response and unanticipated changes in demand in another sector. These factors would limit the effectiveness of a segmental policy. Thus when designing segmental climate policies, it is important not only to set quantitative and coupled targets for technology portfolios and efficiency, but also to anticipate the potential for large error accumulation.

There are potential benefits of a segmental approach stemming from the greater control it allows over the source of emissions reductions. Unlike a cap or tax on carbon, a segmental policy explicitly allocates emissions reductions to the demand and supply side. This may address concerns about the impact of limited foresight and incomplete coordination, which are troubling because these factors may incentivize a focus solely on low-cost, demand-side efficiency improvements while infrastructural inertia continues to grow. We introduce several metrics that demonstrate that infrastructural inertia in the largest emitters—China, the U.S., and Europe—is substantial. The results show that an immediate and dramatic reduction in the supply-side carbon intensity of new-build power plants would be needed over the next decade—more than a 50% reduction in the carbon intensity of new plants as compared to existing infrastructure—to meet emissions targets.

The benefits and drawbacks of the segmental and technology-centered policies that we describe in this paper suggest that there may be advantages to a hybrid approach. The concept of hierarchical control, which has been used in managing complex engineering endeavors,[63] may provide a framework that can be extended to climate policy. A hierarchical policy framework, which combines a cap on carbon and segmental policies applied to all energy sectors, may achieve the efficiency of a carbon-focused instrument, with controls at various levels of sectoral granularity to ensure that necessary changes are occurring in long-lived infrastructure. Quantifying the benefits of a hierarchical approach to climate policy in terms of efficiency and effectiveness is an interesting topic for further research.

■ ASSOCIATED CONTENT

Supporting Information

Additional information on methods and results, as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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The authors declare no competing financial interest.

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