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Energy Technologies Evaluated against Climate Targets Using a Cost and Carbon Trade-off Curve

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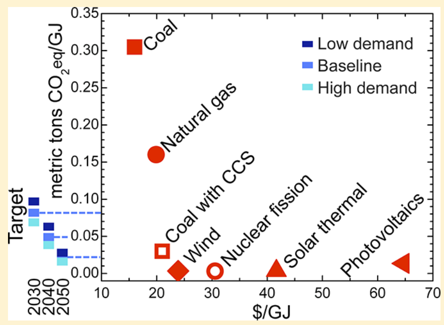
S Supporting Information

ABSTRACT: Over the next few decades, severe cuts in emissions from energy will be required to meet global climate-change mitigation goals. These emission reductions imply a major shift toward low-carbon energy technologies, and the economic cost and technical feasibility of mitigation are therefore highly dependent upon the future performance of energy technologies. However, existing models do not readily translate into quantitative targets against which we can judge the dynamic performance of technologies. Here, we present a simple, new model for evaluating energy-supply technologies and their improvement trajectories against climate-change mitigation goals. We define a target for technology performance in terms of the carbon intensity of energy, consistent with emission reduction goals, and show how the target depends upon energy demand levels. Because the cost of energy determines the level of adoption, we then compare supply technologies to one another and to this target based on their position on a cost and carbon trade-off curve and how the position changes over time. Applying the model to U.S. electricity, we show that the target for carbon intensity will approach zero by midcentury for commonly cited emission reduction goals, even under a high demand-side efficiency scenario. For Chinese electricity, the carbon intensity target is relaxed and less certain because of lesser emission reductions and greater variability in energy demand projections. Examining a century-long database on changes in the cost−carbon space, we find that the magnitude of changes in cost and carbon intensity that are required to meet future performance targets is not unprecedented, providing some evidence that these targets are within engineering reach. The cost and carbon trade-off curve can be used to evaluate the dynamic performance of existing and new technologies against climate-change mitigation goals.



■ INTRODUCTION

The future trajectory of global greenhouse gas emissions will depend upon the level of energy consumption, the carbon emissions per unit energy (carbon intensity of energy), and the emissions from non-energy sectors.[1−5] A number of integrated assessment models have been developed to examine how each of the above variables might evolve with and without policy interventions.[6−8]

These models are used to predict the cost and feasibility of various schemas for climate change mitigation.[9−13] A common approach is to allocate weights to technologies in the energy supply mix to minimize the cost of mitigation while varying the stringency of policies, such as a cap on carbon or a carbon price. The costs and carbon intensities of energy supply technologies that are assumed in the models are major determinants of the cost of mitigation and the optimized supply mix,[14−16] but there remains significant disagreement about how these technology attributes change with time and investment.[15,16] These models estimate the cost of mitigation and optimal pathways for mitigation given a set of assumptions about technology evolution but are not constructed to determine performance targets for technology attributes, such as the cost and carbon intensity of secondary energy.

For engineers and scientists, technology performance targets to reach a given climate target at an acceptable cost are important for guiding design decisions.[17,18] These targets are similarly important for investors in research and development and for policy makers focusing on carbon controls or demand and supply-side specific policies.

Here, we derive performance targets for energy supply technologies to meet emission constraints and show how these targets depend upon future scenarios for energy demand. We propose a new framework for comparing technologies to these targets, which uses a cost and carbon trade-off curve, recognizing that meeting a carbon intensity target in a market-based system requires reducing the cost of low-carbon, high-cost technologies or reducing the carbon intensity of low-cost, high-carbon technologies.

The cost and carbon trade-off curve can be applied at various levels of geographical and sectoral granularity to evaluate energy-supply technologies against climate-change mitigation goals. In this paper, we apply the cost and carbon trade-off

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curve to compare electricity-generating technologies in the U.S. and China to future cost and carbon intensity targets at various points in time. We consider a wide range of demand-side scenarios to investigate a full spectrum of possible changes needed on the supply side.[19] We also show how a price on carbon would change the cost targets and relative competitiveness of technologies, and we compare the historical changes in technologies to the future changes required to reach the performance targets.

The cost and carbon trade-off curve differs from other visual representations of mitigation options, such as the marginal abatement cost curve, which plots the cost of abatement (in dollars per unit of emissions avoided) against the abatement magnitude (emissions avoided).[20] To calculate the abatement cost, the projected average (constant) cost and carbon intensity of a mitigation technology are compared to the business-as-usual alternative. This approach is useful in providing a rough estimate of the scale and cost of various mitigation options, but it does not highlight the underlying assumptions about technology performance on which the results depend nor the relationship between demand and supply-side changes required to meet a given climate target. This paper proposes a complementary, technology-focused framework, which allows for the quantification of aspirational performance intensity targets (performance per unit energy) against which engineers, policy makers, and private investors can evaluate technologies.

The paper is organized as follows. In the next section, we describe methods used for the analysis. We then present results for the carbon intensity and cost targets and show how technologies compare to these performance targets using a cost and carbon trade-off curve.

■ METHODS

Calculating Performance Targets. The carbon intensity target c_t in each year is determined by the allowed carbon emissions C_t and the energy consumption E_t: $c_t = C_t/E_t$. We focus on secondary energy (energy after conversion to a usable form, such as electricity, but before transmission to end users), in order to include conversion efficiency in evaluating technologies and quantifying a performance target. Conversion efficiency is a key driver and engineering control variable for changes in performance over time.

Carbon intensity targets are calculated for the U.S. (Annex I) and China (non-Annex I) in the years 2030, 2040, and 2050. We base emission allocations to Annex I and non-Annex I countries on the discussion in the literature[21−23] for an intended stabilization level of 450 ppm CO_2-equivalent and limiting global warming to 2 °C.[2,6,7] (We note the controversy in determining allocations across countries and the inherent challenge in setting yearly emission targets to be consistent with a given concentration and temperature target.)

Two scenarios were studied, varying the stringency of the emission targets for Annex I and non-Annex I nations to meet a global cap. The modest Annex I emission reduction scenario corresponds to the stricter non-Annex I emission reduction scenario and vice versa. In the first emission allocation scenario (modest Annex I reductions[21,22]), the U.S. reduces emissions to 80% below 1990 levels by 2050 (83% below 2005 levels by 2050) and meets the shorter term emission reduction goal that the U.S. has outlined of 32% below 1990 levels by 2030. The corresponding Chinese emission trajectory reaches a 44% emission reduction below a business-as-usual scenario by 2030 and 75% by 2050. In the second scenario (strict Annex I reductions), U.S. emissions are reduced 55 and 95% below 1990 levels by 2030 and 2050, respectively. Chinese emissions are reduced 33 and 70% below the business-as-usual scenario in 2030 and 2050, respectively. For all scenarios, a fraction of emissions is allocated to the electricity sector based on today's electricity emissions relative to those from other demand sectors. Meeting the overall emission constraint thus requires an equal percent reduction in emissions across all sectors.

High and low electricity consumption scenarios are based on a meta-analysis of demand-side efficiency estimates.[20,24−26] The business-as-usual electricity consumption for the U.S. and China is based on projections by the U.S. Energy Information Agency (EIA).[27] High and low electricity consumption ranges are based on linear growth scenarios, in which demand is 30% above or below the projected baseline consumption in 2050. This range was chosen to represent the upper end of expected deviations from the business-as-usual energy consumption, because of varying degrees of economic growth and demand-side efficiency (although further extremes are possible, particularly in China).[26]

The carbon intensity target depends upon the emission constraint and the energy consumption assumed. A proportional change in C_t or $1/E_t$ will result in the same proportional change in c_t, for small changes. For example, a 10% higher emission target will translate to a 10% higher carbon intensity target.

We also determine cost-competitiveness targets for supplying a given fraction of electricity at baseline costs. (Defining a cost target in a similar way to that of carbon intensity would require a limit set on acceptable expenditures for energy; this is made complicated by differing estimates of the economic impacts of increasing energy costs.[28−31]) Using a simple hourly dispatch model, a yearly demand profile, and a supply mix consisting of natural gas turbines and coal-fired power plants, we estimate a baseline distribution for the cost of electricity.

The cost distribution is based on a sample demand profile, baseline supply mix, and cost of baseline supply technologies. The cost targets incorporate information on hourly changes in electricity costs, improving on cost parity targets that are based on a constant average cost of electricity. The cost targets are rough approximations in that they do not incorporate assumptions about how the supply mix (technologies and their costs) and demand profile will change over time and with location. These changes are difficult to predict, and there is some empirical evidence supporting fluctuating but non-trending electricity costs in recent decades for baseline technologies, such as coal-fired electricity.[32]

Evaluating Technologies. We compare technologies to the cost and carbon intensity targets based on their busbar costs and carbon intensities, averaged over geographical regions, technology designs, and operating conditions. Similar curves could be plotted for particular geographical areas and supply side technology designs.[33,34] On the basis of the carbon intensities of technologies, we determine technology portfolios and associated cost targets to meet carbon intensity targets. The technologies are divided into four categories based on their carbon intensities: carbon-free (renewables and nuclear), natural gas, coal, and coal with carbon capture and storage (CCS). Empirical evidence of flat mean conversion efficiencies for fossil-fuel-fired technologies in recent decades supports treating these carbon intensities as constant;[32] however, further increases in conversion efficiencies (or carbon capture for natural gas) would decrease carbon intensities and increase the fraction of non-carbon-free power in portfolios, by a proportional amount equal to the proportional change in carbon intensity.

To relate past changes in technology performance to future changes needed to reach performance targets, we compile a historical data set on changes to the cost and carbon intensity over time. The historical data are used to estimate the magnitude and rate of past changes to cost and carbon intensity.

RESULTS

Here, we present carbon intensity and cost targets for electricity that are consistent with climate goals and show how these change over time (from 2030 to 2050) and with location (for China and the U.S.). We then use a cost and carbon trade-off curve and changes to this curve over time to compare technologies to these targets.

Carbon Intensity Target. Carbon intensity targets for U.S. and Chinese electricity are shown in Figure 1 for two emission allocation scenarios and the same global emission reduction target.[21,22] There are several notable aspects of how these targets change over time and space.

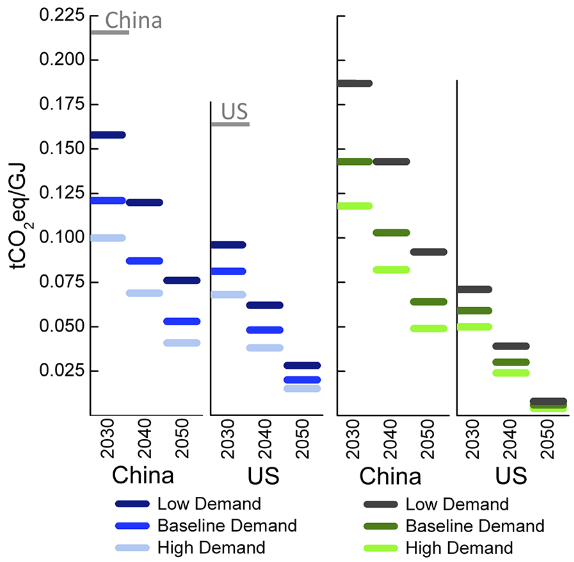

Figure 1. Carbon intensity targets for the U.S. (Annex I) and China (non-Annex I). Two emission allocation scenarios are shown for (left) modest Annex I emission caps and stricter non-Annex I emission caps and (right) strict Annex I emission caps and more lenient non-Annex I emission caps. The carbon intensity target range in each year depends upon electricity consumption, with higher carbon intensity targets corresponding to lower electricity consumption. Gray lines show estimates of current carbon intensities of electricity.

The carbon intensity targets are substantially lower for the U.S. than for China. As expected, this difference between the two nations is greatest for the strict Annex I scenario, where emission allowances differ the most. The difference is reduced over time as the emission allowances converge, and by 2050, the carbon intensity targets are similar across the two nations.

Also, the certainty in the carbon intensity target in the U.S. is greater than in China, because of a stricter emission reduction target in the U.S. and a less variable consumption projection. The increasing target stringency decreases the variability in carbon intensity targets that derives from differences in energy consumption projections. The greater uncertainty in Chinese electricity demand in combination with a less strict carbon emission reduction target translates into a greater variability in the Chinese carbon intensity targets.

The variability in the carbon intensity targets decreases over time for both nations, again because of an increase in emission target stringency. The increasing stringency overcompensates for the increasing variability in demand projections over time. For both countries, the carbon intensity target is constrained to a narrow range of values close to zero by midcentury. This implies that a major transformation is needed in the energy supply infrastructure by midcentury to meet these climate targets, regardless of demand levels.

In earlier decades, however, energy efficiency will allow for substantial extra time for a supply-side transformation. For example, the low energy consumption scenario for China (an extreme demand-side efficiency scenario) buys roughly one decade of extra time to reach the 2030 carbon intensity target for the baseline consumption scenario. The duration of the buffer afforded by demand-side efficiency is reduced over time as the effect of the energy savings on the carbon intensity target is overtaken by that of the decreasing emission allowance. The amount of extra time afforded by energy efficiency is less for the U.S. than for China in all years for the same reason.

We note that if there is a global carbon market, and emission reductions are implemented across national borders, the carbon intensity could be fairly uniform across the globe in all years. Furthermore, technology improvement and cost decreases resulting from efforts to meet emission reduction targets by Annex I countries could lead to greater than required adoption of low-carbon technologies by non-Annex I countries. Therefore, taking a technology-focused perspective and recognizing the improving performance of technologies with adoption may help in moving beyond the current impasse in global negotiations on developed and developing country emission goals.

Cost Target. We use a sample load profile and set of installed power plants (Figure 2) to determine a distribution of hourly electricity costs. This gives a roughly approximated

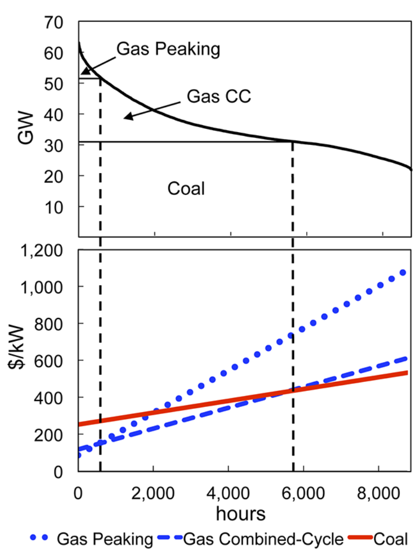

Figure 2. Screening curve for a baseline demand profile and supply mix. The supply mix includes natural gas turbines and coal-fired power plants.

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distribution of baseline cost targets (Figure 3), for electric power that can be dispatched at will or where the availability of

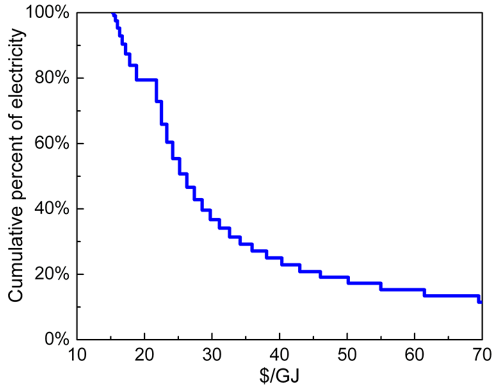

Figure 3. Electricity cost distribution, assuming the baseline screening curve and demand profile in Figure 2. The *y* axis shows the percentage of electricity consumption for which costs are greater than the *x*-axis values. For reference, \$20/GJ = \$0.072/kWh.

a renewable resource coincides with demand. Figure 3 shows, for example, that electricity at a cost of \$45/GJ (or \$0.162/kWh) would be competitive relative to the baseline up to a penetration level of 20%.

The cost target can be considered an environmental performance target, because it will determine which technologies are adopted and the carbon intensity of the fleet. For each carbon intensity, there is an associated (approximated) cost target for technology portfolios. For example, if the carbon intensity requires 50% of power from carbon-free technologies, the cost of electricity of candidate carbon-free technologies needs to reach the 50% cost target for cost-competitiveness of approximately \$25/GJ or \$0.090/kWh (Figure 3).

Comparing Technologies to Performance Targets Using a Cost and Carbon Trade-off Curve. We propose a cost and carbon trade-off curve to compare technologies to one another and to climate targets. The costs and carbon intensities for electricity-generating technologies are shown in Figure 4. The shape of the cost and carbon curve indicates the current trade-off between cost and carbon intensity, where the lowest cost technologies, natural gas and coal, are highest in carbon intensity.

Several current technologies are within the range of the long-term targets for carbon intensity (Figure 4). These include photovoltaics, solar thermal, nuclear fission, and wind. While the carbon intensity for photovoltaics is higher than for nuclear fission, wind, or solar thermal, indicating greater energy consumption for manufacturing, the carbon intensity of all of these technologies will tend to zero as the energy supply mix is decarbonized. Therefore, it is reasonable to consider these technologies "carbon-free" in mitigation portfolios. This is not the case for technologies with substantial operating emissions, including natural-gas- and coal-fired electricity.

For technologies with operating emissions, carbon capture and storage (CCS) would be required to reduce the carbon intensity below that of the fuel. However, the emissions can be significant even after capture when compared to the very low carbon intensities needed by midcentury to meet emission targets in Annex I countries. Figure 4 shows a cost and carbon intensity estimate for coal with CCS. Assuming a 90% capture efficiency, the carbon intensity of coal with CCS is projected to

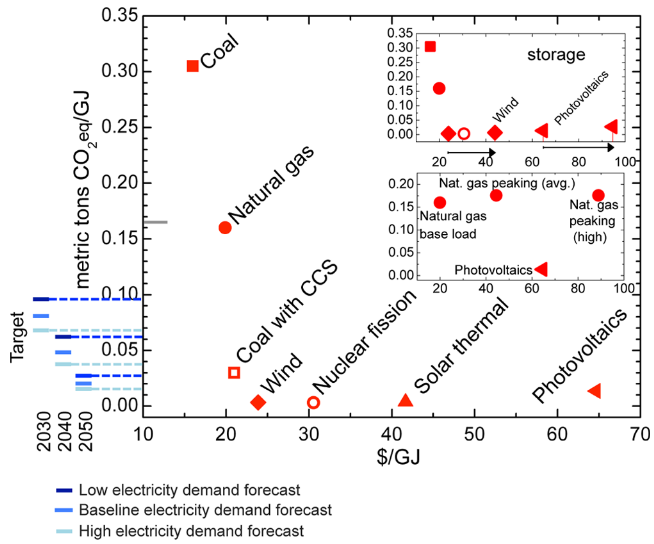

Figure 4. Cost and carbon trade-off curve for electricity. Points are average life-cycle busbar costs and carbon intensities. The cost and carbon intensity of coal with CCS are projections. The gray line is the U.S. weighted average carbon intensity of electricity. The carbon intensity targets (blue lines) shown are for U.S. electricity and a modest Annex I emission allocation scenario. (Bottom inset) Estimate of the increase in electricity costs for natural gas peaking plants and a comparison to photovoltaics. (Top inset) Added costs of storage for wind, photovoltaics, and solar thermal. For reference, \$20/GJ = \$0.072/kWh.

meet the upper end of the target range for U.S. electricity by 2050, which is derived from the lower end of the projected range for electricity consumption and the less strict Annex I emission reduction scenario (Figure 4). Comparing the target for the weighted average carbon intensity to the carbon intensity of coal with CCS allows for a visual estimate of the fraction of electricity consumption that can be supplied by coal with CCS in any portfolio. For much of the target range, coal with CCS in a portfolio will need to be supplemented by carbon-free technologies.

The costs and carbon intensities of a technology within a particular class (coal, natural gas, solar, etc.) vary with plant efficiency and other design features. These quantities also change with the capacity factor, which depends upon the availability of the renewable energy resource (for renewable energy conversion) and the electricity demand profile (for dispatchable power). As the capacity factor decreases for peaking plants, for example, the costs will increase relative to a plant that has a higher capacity factor (bottom inset of Figure 4).

A carbon price to internalize the external costs of emissions would change the trade-off curve and the cost target to reach a given carbon intensity target (Figure 5). A carbon price would decrease the amount of improvement needed in high-cost, low-carbon technologies to reach cost competitiveness with fossil fuels. The greater the carbon price, the less cost improvement needed to reach a given carbon intensity target.

The cost and carbon curve allows us to visualize the impact of a carbon price on various technologies. We can define a relative carbon price risk factor as the proportional amount by which the carbon intensities of technologies differ from one another. The carbon intensity of coal is roughly twice that of natural gas and more than 30 times that of renewable energy technologies; therefore, the relative carbon price risk factor for

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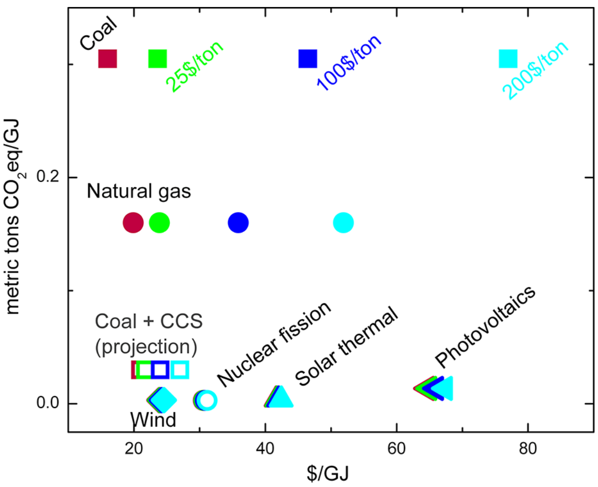

Figure 5. Impact of a carbon price on the cost and carbon trade-off curve for electricity. A price on carbon changes the rank ordering of the cost-competitiveness of technologies.

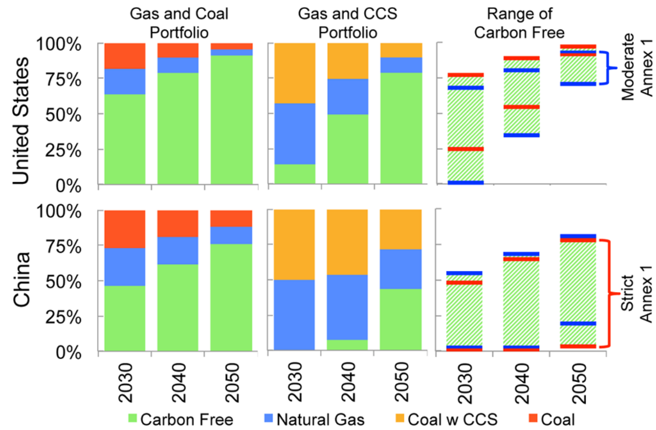

Figure 6. Portfolios to meet carbon intensity targets. The impact of the emission allocation scenario, the energy demand, and the energy mix on the amount of carbon-free power required is shown. Portfolios shown in the left and middle columns are for a baseline electricity demand and a modest Annex I emission reduction scenario. The carbon-free power required for the full range of energy consumption scenarios is shown in the right column, for both a moderate and a strict Annex I emission reduction scenario. The upper end of the estimated carbon-free power needed corresponds to a high demand scenario and a portfolio with equal shares of natural gas and coal. The lower end of the range corresponds to a low energy demand scenario and a portfolio with equal allocation to natural gas and coal with CCS.

coal compared to natural gas is roughly equal to 2 and is roughly 30 compared to renewable energy. This risk factor determines how the additional cost incurred as a result of a carbon price scales across technologies. The total electricity cost is the sum of this additional cost and the cost of energy. Because of differences in the carbon price risk factor, the rank ordering of total electricity costs changes with the carbon price (Figure 5).

Portfolios. Moving beyond a focus on individual technologies, we ask which technology portfolios would meet carbon intensity targets in the U.S. and in China. We distinguish between the following broad classes of technologies based on their carbon intensities: coal, coal with CCS, natural gas, and carbon-free technologies (renewables and nuclear). Two sample portfolio formulations are explored: (1) coal and natural gas supply equal shares of total electricity, and (2) coal with CCS and natural gas supply equal shares of electricity. In both formulations, the share of fossil-fuel-generated electricity is maximized and supplemented by carbon-free generation to meet the carbon intensity target.

The energy resource size for each technology imposes an upper limit on the energy that it is able to supply. Estimates of energy resource sizes for each technology shown on the cost and carbon trade-off curve vary widely across studies depending upon the assumptions that are made about practical scalability.[35−41] On the basis of the energy resource size and geographical distribution or ease of transportation with currently available methods, photovoltaics, coal, and nuclear emerge as frontrunners in terms of resource availability. Updated estimates of natural gas reserves, which include expanded reserves for shale gas deposits, are also substantial.[42] Resource sizes of each of the three broad classes of technologies considered here are expected to be sufficient to meet the portfolios outlined in this section.

Sample portfolios for the U.S. and China are shown in Figure 6. For the moderate Annex I emission reduction scenario of 80% below 1990 levels by 2050 applied to the U.S. and a baseline electricity demand projection, carbon-free technologies would need to supply approximately 65, 80, and 90% of electricity in 2030, 2040, and 2050, respectively, if the rest is supplied by equal shares of coal and natural gas. We can estimate a rough cost target for dispatchable carbon-free technologies of 23, 19, and $16/GJ (or 0.083, 0.068, and $0.058/kWh) to achieve these portfolios without exceeding the baseline electricity cost distribution shown in Figure 3. In China, for the corresponding emission reduction scenario, carbon-free technologies would need to supply approximately 45, 60, and 75% in 2030, 2040, and 2050, respectively. The approximate cost target would be 28, 24, and $22/GJ (or 0.101, 0.086, and $0.079/kWh) for carbon-free technologies (Figure 3). Using these portfolio cost targets, we can return to the cost and carbon trade-off curve to evaluate carbon-free technologies (Figure 4).

The multiple scenarios investigated in this analysis, varying future electricity demand, emission allocations to Annex I and non-Annex I countries, and portfolio formulations, allow us to analyze the range of carbon-free generation that will be needed to meet emission reduction goals (Figure 6). The upper end of the range of carbon-free power needed is based on the high demand scenario and the portfolio with equal shares of natural gas and coal. The lower end of the range is defined by the low energy demand scenario and a portfolio with equal allocation to natural gas and coal with CCS.

For U.S. electricity, even under a low energy demand scenario and a high emission allocation scenario, major decarbonization is needed by 2050 (70% or above). For Chinese electricity, major decarbonization is needed to meet emission reductions for a modest Annex I emission allocation scenario and a baseline electricity demand, assuming a portfolio with coal and natural gas (45, 60, and 75% in 2030, 2040, and 2050, respectively). In contrast, for a baseline demand and a portfolio with natural gas and coal with CCS, the carbon-free power needed is reduced to approximately 0, 10, and 45% in 2030, 2040, and 2050, respectively. For higher emission allocations, extremely low demand projections, and a portfolio with natural gas and coal with CCS, minimal amounts of carbon-free power are needed in China to meet the carbon intensity targets. This greater variability in the carbon intensity

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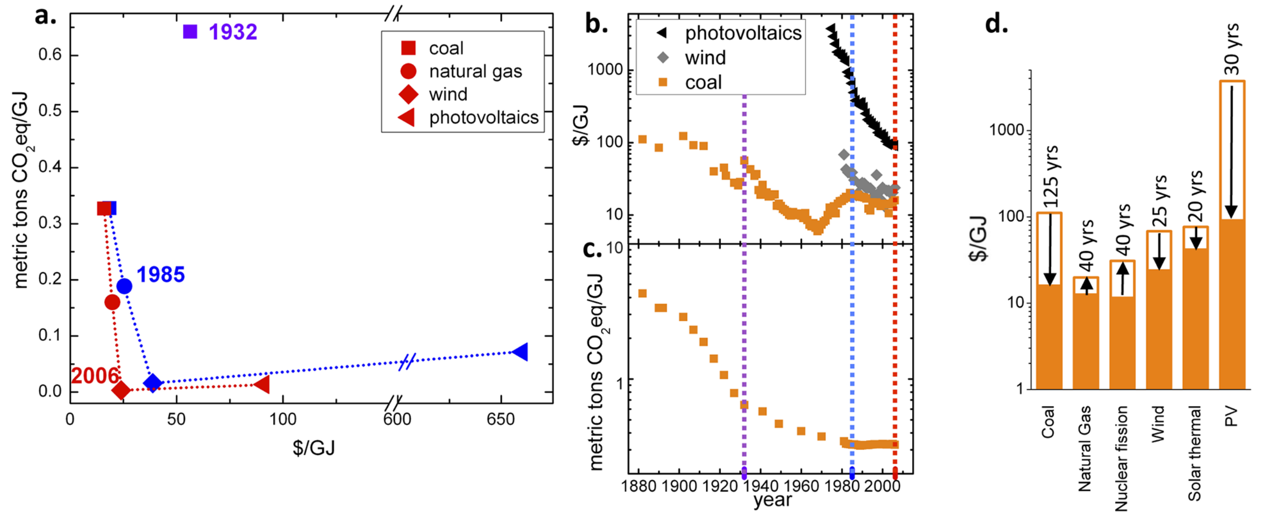

Figure 7. Historical changes in performance. (a) The cost and carbon trade-off curve has contracted over time to the low-cost, low-carbon corner. Note the break in the cost axis. A dynamic graph is available online in the Supporting Information, where the size of the points represents the fraction of U.S. electricity demand met by the technology. (b) Photovoltaics (PV) has changed the most and fastest along the cost-intensity axis. Colored vertical lines indicate the years plotted in panel a. (c) Coal has changed the most along the carbon-intensity axis but not in recent decades. (d) Wind, solar thermal, and PV have decreased in cost more than the additional decrease needed to reach the current cost of coal electricity ($16/GJ). Relative lengths of the outlined orange bars and the solid orange bars up to the cost competitive point with coal-fired electricity can be used to estimate the years to reach competitiveness with coal, assuming declining cost at a constant exponential rate (and a constant cost of coal electricity). This is an approximation because the rate has changed over time (see panel b). Nuclear fission and natural gas electricity costs increased over the time period considered. Nuclear costs followed a steady increasing trend, whereas the natural gas costs fluctuated significantly. For reference, $20/GJ = $0.072/kWh.

target and associated climate-goal compliant portfolios in China is due to the greater emission allocations and greater variability in energy demand projections.

Historical Context. History provides additional perspective on the prospects for reaching the cost and carbon intensity targets. Technologies have moved around significantly in the cost and carbon space since the early years of electrification in the 1880s (Figure 7).

Past changes are comparable to the future changes required to reach the carbon intensity target shown in Figure 4, in the following sense. The target can be reached by either decreases in the carbon intensity of low-cost technologies or decreases in the cost of low-carbon technologies. Along both the cost and carbon axes, there is a technology that has changed in the past as much or more than necessary in the future to reach the carbon intensity target and associated cost target. A comparison of the shape of the trade-off curves for the years 1985 and 2006 indicates that in recent decades there has been more change along the cost axis than the carbon intensity axis.

Coal-based electricity accounts for the greatest change in carbon intensity within any technology (Figure 7). Between the years 1882 and 1960, the average efficiency of coal-fired power plants increased from roughly 3 to 30%, with an attendant reduction in carbon intensity.[32] However, the carbon intensity has not changed much over the last 50 years, because the mean conversion efficiency from primary to secondary energy has remained relatively flat.

Photovoltaics account for the greatest magnitude and highest rate of change in cost of all technologies studied (Figure 7). Along the cost axis, this technology has changed significantly more to date than it would need to further decline to reach cost competitiveness with coal-fired electricity (Figure 7).

The costs of many technologies follow roughly exponential declines, meaning that absolute changes slow down with time (Figure 7). A continuation of the historical rate of change in the cost of photovoltaics and wind, for example, would mean that these technologies coupled with storage would become cost-competitive with coal between 2030 and 2050, if one assumes the cost of storage reaches $10/GJ (see the Supporting Information). The time needed to reach other portfolio cost targets, based on historical improvement rates, can also be estimated using Figure 7. However, policy to fund research and development and create ongoing growth opportunities will likely be needed to sustain the historical rates of change for these technologies.

DISCUSSION

The cost and carbon trade-off curve allows us to evaluate energy supply technologies and their innovation trajectories against climate targets under wide-ranging assumptions about demand-side energy efficiency. Notably, we show for the case of U.S. electricity that the target range for carbon intensity is narrowly defined and will approach zero by midcentury for commonly cited emission reduction goals, even under a high demand-side efficiency scenario. For Chinese electricity, the cost and carbon intensity targets are relaxed and less certain because of lesser emission reductions and greater variability in energy demand projections.

In both China and the U.S., high demand-side efficiency can buy extra time for a transition to carbon-free power, up to one decade of extra time in the Chinese case investigated. Eventually, though, the increasing stringency of emission reduction goals will require a complete decarbonization of supply-side technologies, regardless of demand-side efficiency. The carbon intensity targets presented here are based on a very wide range of demand assumptions and are, therefore, quite robust to changes in assumptions about the demand-side efficiency potential. As the emission target approaches zero, major decreases in the carbon intensity of the energy supply are

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needed. This is because the carbon intensity is the only determinant of emissions that can approach zero ($C_t = E_t c_t$, where C_t is emissions, E_t is energy and c_t is carbon intensity). In China, the less strict emission reduction target extends the time horizon for this transition. A less stringent global climate target would extend this timeline for all nations.

Technologies exist that are well within the long term carbon intensity target ranges. However, as we show, some technologies that are considered mitigation options, such as coal with a 90% efficient carbon capture system, are above the mean U.S. carbon intensity target by 2050, and their use would need to be balanced by carbon-free power to meet the target.

For each carbon intensity target, we determine an approximate cost target and compare historical changes to technology performance to these future targets using a cost and carbon trade-off curve. Importantly, our analysis shows that historical changes in cost and carbon intensity are comparable to those needed going forward to achieve the climate-goal compliant portfolios, providing some reason for optimism regarding prospects for reaching future targets. However, continued policy support is likely needed to sustain the historical rate of adoption and improvement going forward. Policies, such as a price on carbon, research and development (R&D) funding, and guaranteed markets (such as renewable portfolio standards), may also increase the rate of change.[16,43,44]

This study focuses on the electricity sector, but other trade-off curves could be plotted for transportation and direct heating. The framework developed can be used to study other energy-related sustainability challenges, such as land use and water intensity, by linking quantitative performance targets, trade-offs, and the dynamics of technological change. On the basis of the availability of land and the aridity, region-specific limits on impact could be set (similar to the carbon emission allowances) and performance targets for water intensity and land use intensity could be determined for energy technologies (similar to the carbon intensity targets).

Targets for technology attributes that are influenced by R&D choices, and a way to compare technologies to these targets, are needed to inform engineering design, policy design, and private investment decisions. Scientists and engineers developing new technologies can use the model presented here to inform design choices, such as how to balance the trade-off between greater capture efficiency and increased cost of carbon capture systems. Cost targets may inform the choice of materials and processing methods for photovoltaics and storage. Investors can use the trade-off curve to assess the carbon price risk associated with various technologies. Policy makers can use the cost and carbon trade-off curve to monitor the improvement rate of technologies in comparison to climate-change mitigation goals.

■ ASSOCIATED CONTENT

Supporting Information

Carbon intensity targets (S1), cost targets (S2), technology costs, carbon intensities, and resource sizes (S3), and technology trajectories (S4). A dynamic graph explained in Figure 7 is available in the online version of this paper. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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