Greenhouse gases, climate change and the transition from coal to low-carbon electricity

Greenhouse gases, climate change and the transition from coal to low-carbon electricity

N P Myhrvold[1] and K Caldeira[2]

[1] Intellectual Ventures, Bellevue, WA 98005, USA
[2] Department of Global Ecology, Carnegie Institution, Stanford, CA 94305, USA

E-mail: kcaldeira@carnegie.stanford.edu

Abstract

A transition from the global system of coal-based electricity generation to
low-greenhouse-gas-emission energy technologies is required to mitigate climate change in
the long term. The use of current infrastructure to build this new low-emission system
necessitates additional emissions of greenhouse gases, and the coal-based infrastructure will
continue to emit substantial amounts of greenhouse gases as it is phased out. Furthermore,
ocean thermal inertia delays the climate benefits of emissions reductions. By constructing a
quantitative model of energy system transitions that includes life-cycle emissions and the
central physics of greenhouse warming, we estimate the global warming expected to occur as
a result of build-outs of new energy technologies ranging from 100 GW_e to 10 TW_e in size
and 1–100 yr in duration. We show that rapid deployment of low-emission energy systems can
do little to diminish the climate impacts in the first half of this century. Conservation, wind,
solar, nuclear power, and possibly carbon capture and storage appear to be able to achieve
substantial climate benefits in the second half of this century; however, natural gas cannot.

1. Introduction

Hoffert *et al* [1] estimated that if economic growth continues as it has in the past, 10–30 TW of carbon-neutral primary power must be deployed by 2050 to meet global energy demand while stabilizing CO_2 concentrations at 450 ppmv, and that even more rapid deployment of new technologies would need to occur in the second half of this century. Pacala and Socolow [2] have suggested that a broad portfolio of existing technologies could put us on a trajectory toward stabilization in the first half of this century. No previous study, however, has predicted the climate effects of energy system transitions.

Fossil fuels, such as coal and natural gas, emit greenhouse gases when burned in conventional power plants. Concern about climate change has motivated the deployment of lower-GHG-emission (LGE) power plants, including wind, solar photovoltaics (PV), nuclear, solar thermal, hydroelectric, carbon capture and storage, natural gas and other energy technologies with low GHG emissions. Electricity generation accounts for approximately 39% of anthropogenic carbon dioxide emissions [3, 4].

Because LGE power plants have lower operating emissions, cumulative emissions over the lifetime of the plants are lower than for conventional fossil-fueled plants of equivalent capacity. LGE power plants typically require greater upfront emissions to build, however. Consequently,

rapid deployment of a fleet of LGE power plants could initially increase cumulative emissions and global mean surface temperatures over what would occur if the same net electrical output were generated by conventional coal-fired plants. Our results show that most of the climate benefit of a transition to LGE energy systems will appear only after the transition is complete. This substantial delay has implications for policy aimed at moderating climate impacts of the electricity generation sector.

2. Models of LGE energy system build-outs

To make our assumptions clear and explicit, we used simple mathematical models to investigate the transient effects of energy system transitions on GHG concentrations, radiative forcing and global mean temperature changes. We represent an electric power plant's life in two phases: construction and operation. Our model assumes that each plant produces a constant annual rate of GHG emissions as it is constructed and a different constant emission rate as it operates. Emission rates were taken from the literature (see table S1 in the supplementary online material (SOM) available at stacks.iop.org/ERL/7/014019/mmedia). IPCC-published formulas for the atmospheric lifetime of GHGs [5] are used to model increases in atmospheric GHG concentrations that result from the construction and operation of each power plant (see SOM text SE1 for details). Radiative forcing as a function of time, $\Delta F(t)$, follows directly from GHG concentration using expressions from the IPCC [5].

We estimated the change in surface temperature, ΔT by using a simple energy-balance model. The radiative forcing ΔF supplies additional energy into the system. Radiative losses to space are determined by a climate feedback parameter, λ. We used $\lambda = 1.25$ W m^2 K^{-1} [6–8], which yields an equilibrium warming of 3.18 K resulting from the radiative forcing that follows a doubling of atmospheric CO_2 from 280 to 560 ppmv. The approach to equilibrium warming is delayed by the thermal inertia of the oceans. We represented the oceans as a 4 km thick, diffusive slab with a vertical thermal diffusivity $k_v = 10^{-4}$ m^2 s^{-1} [8]. Other parameter choices are possible, but variations within reason would not change our qualitative results, and this approach is supported by recent tests with three-dimensional models of the global climate response to periodic forcing [9]. Our simple climate model treats direct thermal heating in the same way as radiative heating; heat either mixes downward into the ocean or radiates outward to space. To isolate the effects of a transition to LGE energy systems, we consider GHG emissions from only the power plant transition studied. Initial, steady-state atmospheric GHG concentrations are set to $P_{CO_2} = 400$ ppmv, $P_{CH_4} = 1800$ ppbv, and $P_{N_2O} = 320$ ppbv, at which $\Delta F = \Delta T = 0$. (Use of other background concentrations for GHGs would not alter our qualitative results (SOM text SE1.3 available at stacks.iop.org/ERL/7/014019/mmedia)).

Although life-cycle estimates of emissions from individual power plants (SOM table S1 available at stacks.iop.org/ERL/7/014019/mmedia) vary, they show a consistent pattern

at both the low and high ends of the range, as seen in figures 1(A) and (B). For renewable plants, peak emissions occur during plant construction. For fossil-fueled plants, in contrast, operating emissions dominate; typically <1% of lifetime plant emissions are attributable to construction. For nuclear plants, both construction and fueling for ongoing operation make substantial contributions to lifetime GHG emissions, although these emissions are far lower than the emissions from coal-fired power plants. The primary GHG emission from hydroelectric plants is methane (CH_4) produced by anaerobic decay of organic matter that is inundated as the reservoir fills [10–12]; the amount emitted varies with local conditions.

To provide a stable supply of electricity, a new power plant must be built as each old power plant nears the end of its useful life. As shown in figures 1(C) and (D), fossil-fueled plants produce a comparatively smooth increase in atmospheric GHG concentrations because emissions during construction are small compared to those from operations. In contrast, the larger contribution during construction of nuclear and renewable power plants produces increased emissions each time a plant of this kind is replaced, yielding a sawtooth trend in atmospheric GHG concentrations for a constant output of electricity.

Construction and operation of a new power plant of any technology modeled here will produce higher atmospheric CO_2 concentrations than would have occurred if no new generating capacity were added. Carbon dioxide poses a special concern because of its long lifetime in the atmosphere. With the exception of dams, carbon dioxide emissions dominate the GHG radiative forcing from power plants. Radiative forcing due to CH_4 and N_2O at any point in time accounts for <1% of the total GHG forcing from wind, solar and nuclear power plants; <5% for coal-fired plants; and <10% for natural gas plants. CH_4 dominates only in the case of hydroelectric power, for which it contributes ∼95% of the radiative forcing in the first 20 yr, declining monotonically to ∼50% at 70 yr after construction.

We contrasted LGE energy technologies with a high-GHG-emission (HGE) energy technology, namely conventional coal-based electricity production. We define 'HGE warming' to mean the increase in global mean surface temperature that would have been produced by the continued operation of the coal-based HGE energy system. This warming is additional to any temperature increases occurring as a result of past or concurrent emissions from outside the 1 TW$_e$ energy system considered here.

To illustrate the consequences of rapid deployments of new energy systems, we considered emissions from a variety of linear energy system transitions, each of which replaces 1 TW$_e$ of coal-based electricity by bringing new LGE power plants online at a constant rate over a 40 yr period. (1 TW$_e$ is the order of magnitude of the global electrical output currently generated from coal [10].) Existing coal-fired generators were assumed to be new at the onset of the transition, to be replaced with equivalent plants at the end of their lifetime, and to be retired at the rate of new plant additions in order to maintain constant annual output of electricity. Lifetimes
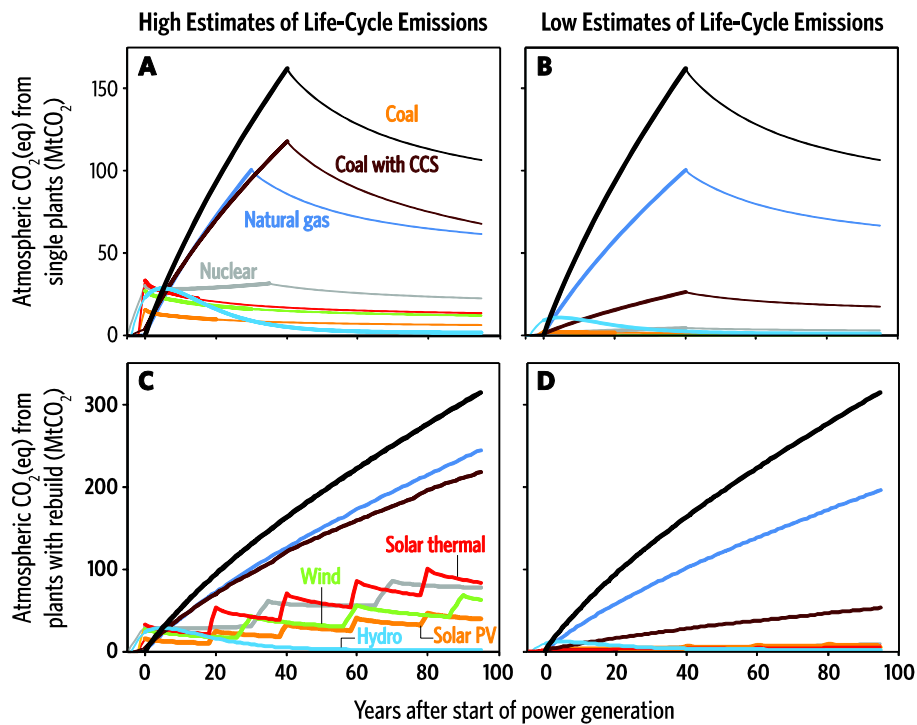
Figure 1. The time evolution of atmospheric CO_2(eq) concentrations resulting from the construction and operation of a 1 GW$_e$ electric power plant varies widely depending on the type of plant. (A), (B) Atmospheric CO_2(eq) concentrations from single power plants of different types based on high (A) and low (B) estimates of life-cycle power plant emissions. Renewable technologies have higher emissions in the construction phase (thin lines prior to year zero); conventional fossil technologies have higher emissions while operating (thick lines); emitted gases persist in the atmosphere even after cessation of operation (thin lines after year zero). The operating life of plants varies by plant type. (C), (D) Atmospheric CO_2(eq) concentrations from the construction of series of power plants built to maintain 1 GW$_e$ output. For high estimates of life-cycle emissions, periodic replacement of aging plants produces pulses of emissions resulting in substantial, step-like change in atmospheric concentrations. However, in all cases except hydroelectric, continued electricity production results in increasing trends of atmospheric CO_2(eq) concentrations.

and thermal efficiencies of the coal plants were taken from the life-cycle analysis (LCA) literature, as were the additional emissions associated with constructing power plants (SOM table S1 available at stacks.iop.org/ERL/7/014019/mmedia). Using GHG emission data from this literature, we calculated time series for emissions, radiative forcing, and temperature for build-outs of eight LGE energy technologies, for a range of rollout durations (SOM text SN3 available at stacks.iop.org/ERL/7/014019/mmedia) including, as a lower bound, the unrealistic case in which all plants are built simultaneously in a single year. Climate consequences of a portfolio of technologies can be approximated by a linear combination of our results for each technology taken individually. For each technology, we examine low and high emission estimates from the LCA literature, and label these 'Low' and 'High'. The time evolution of emissions and temperature increases resulting from an example transition, from coal to natural gas, is illustrated in SOM table S4 (available at stacks.iop.org/ERL/7/014019/mmedia).

We investigated transitions from an HGE energy system to various LGE options for a wide range of transition rates (figure 4). Building on previous life-cycle analyses (SOM table S1 available at stacks.iop.org/ERL/7/014019/mmedia), we estimated the magnitude of most direct and indirect GHG emissions from the construction and operation of

the power plants, including GHG emissions associated with long-distance electricity transmission and thermal emissions attributable to power generation and use (SOM text SN2 available at stacks.iop.org/ERL/7/014019/mmedia). During this transition, GHG emissions attributed to the fleet include both those due to construction or operation of the new technology and those due to coal-fired generators that have not yet been replaced. Various energy system transitions could be imagined. Delaying the transition delays long-term climate benefits of LGE energy. Accelerating the transition decreases total fleet emissions from burning coal, but increases the rate of emissions produced by new construction (figure 4(C)). Qualitatively similar results hold for exponential and logistic growth trajectories (SOM text SD1 and figures S10–12 available at stacks.iop.org/ERL/7/014019/mmedia).

3. Delayed benefits from energy system transitions

By the time any new power plant begins generating electricity, it has incurred an 'emissions debt' equal to the GHGs released to the atmosphere during its construction. The size of this debt varies from one LGE technology to another, as does the operating time required to reach a break-even point at which emissions avoided by displacing power from an HGE plant equal the emissions debt. All transitions from coal to other energy technologies thus show higher GHG concentrations
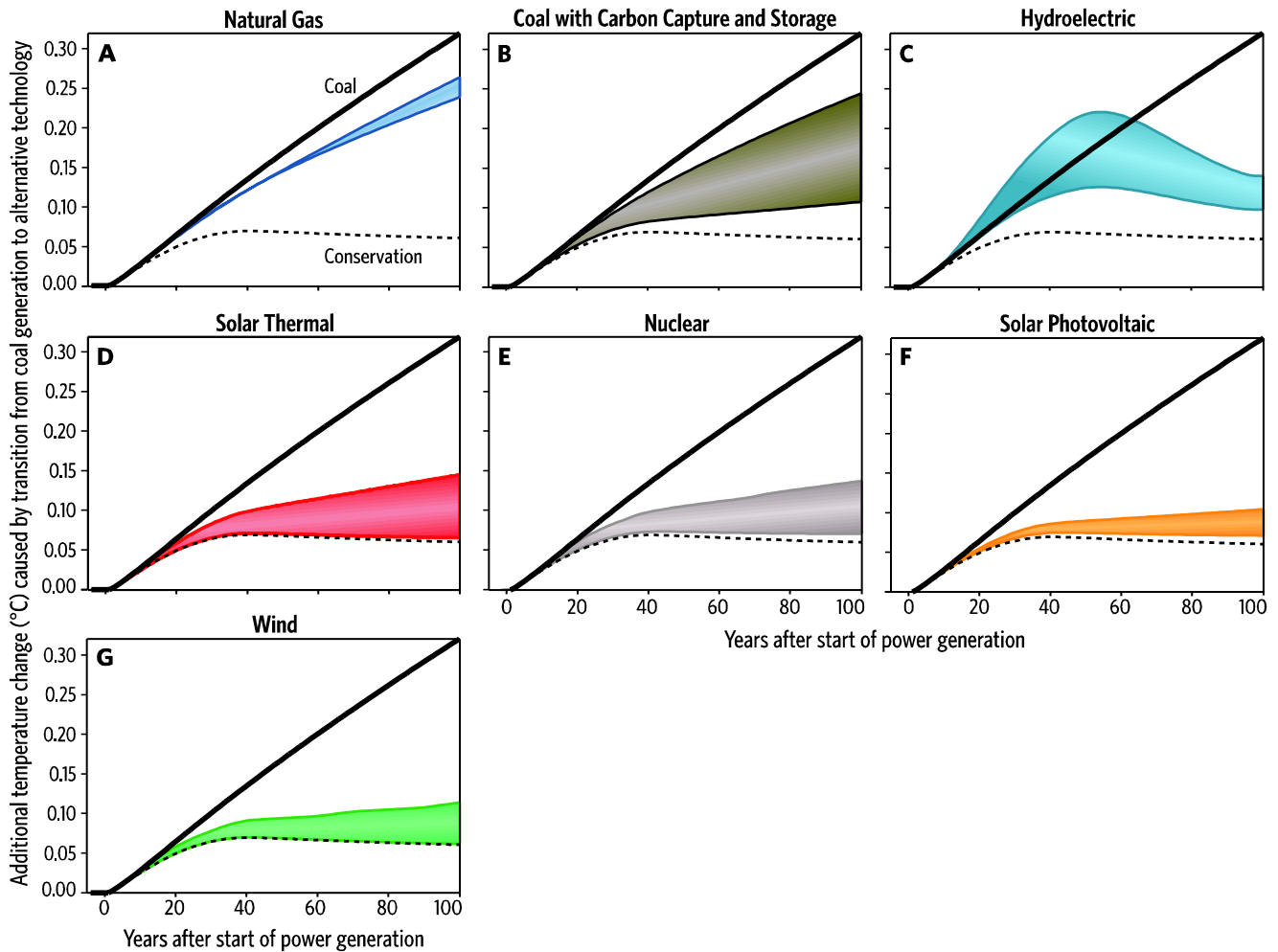
Figure 2. Many decades may pass before a transition from coal-based electricity to alternative generation technologies yields substantial temperature benefits. Panels above show the temperature increases predicted to occur during a 40 yr transition of 1 TW_e of generating capacity. Warming resulting from continued coal use with no alternative technology sets an upper bound (solid black lines), and the temperature increase predicted to occur even if coal were replaced by idealized conservation with zero CO_2 emissions (dashed lines) represents a lower bound. The colored bands represent the range of warming outcomes spanned by high and low life-cycle estimates for the energy technologies illustrated: (A) natural gas, (B) coal with carbon capture and storage, (C) hydroelectric, (D) solar thermal, (E) nuclear, (F) solar photovoltaic and (G) wind.

and temperatures at the outset than would have occurred in the absence of a transition to a new energy system. We calculated, for each technology, the number of years following the start of electricity generation until the transition starts reducing HGE warming, as well as the times at which the transition has reduced HGE warming by 25% or 50%.

Our results (figure 2 and SOM tables S3 and S4 available at stacks.iop.org/ERL/7/014019/mmedia) illustrate the general finding that emerges from our results: energy system transitions cause reductions in HGE warming only once they are well underway, and it takes much longer still for any new system to deliver substantial climate benefits over a conventional coal-based system. It is instructive to examine idealized energy conservation, considered here as a technology that produces electricity with zero GHG emissions. Conservation is thus equivalent to phasing out 1 TW_e of coal power over 40 yr without any replacement technology. Even in this case, GHGs (particularly CO_2) emitted by coal during the phaseout linger in the atmosphere

for many years; in addition, ocean thermal inertia causes temperature changes to lag radiative forcing changes. Consequently, conservation takes 20 yr to achieve a 25% reduction in HGE warming and 40 yr to achieve a 50% reduction.

This idealized rollout of conservation that displaces 1 TW_e of conventional coal power sets a lower bound to the temperature reductions attainable by any technology that does not actively withdraw GHGs from the atmosphere. This lower bound is approached most closely by wind, solar thermal, solar PV and nuclear, using the low LCA estimates; these cases yield temperature increases that exceed the idealized conservation case by only a fraction of a degree, and the time to a 50% reduction in HGE warming is delayed by only a few years. Differences among these same technologies appear, however, if high LCA estimates are used (figure 3). When using the complete range of LCA estimates, for example, our model projects that a 40 yr, linear transition from coal to solar PV would cause a 1.4–6.9 yr period with greater warming than
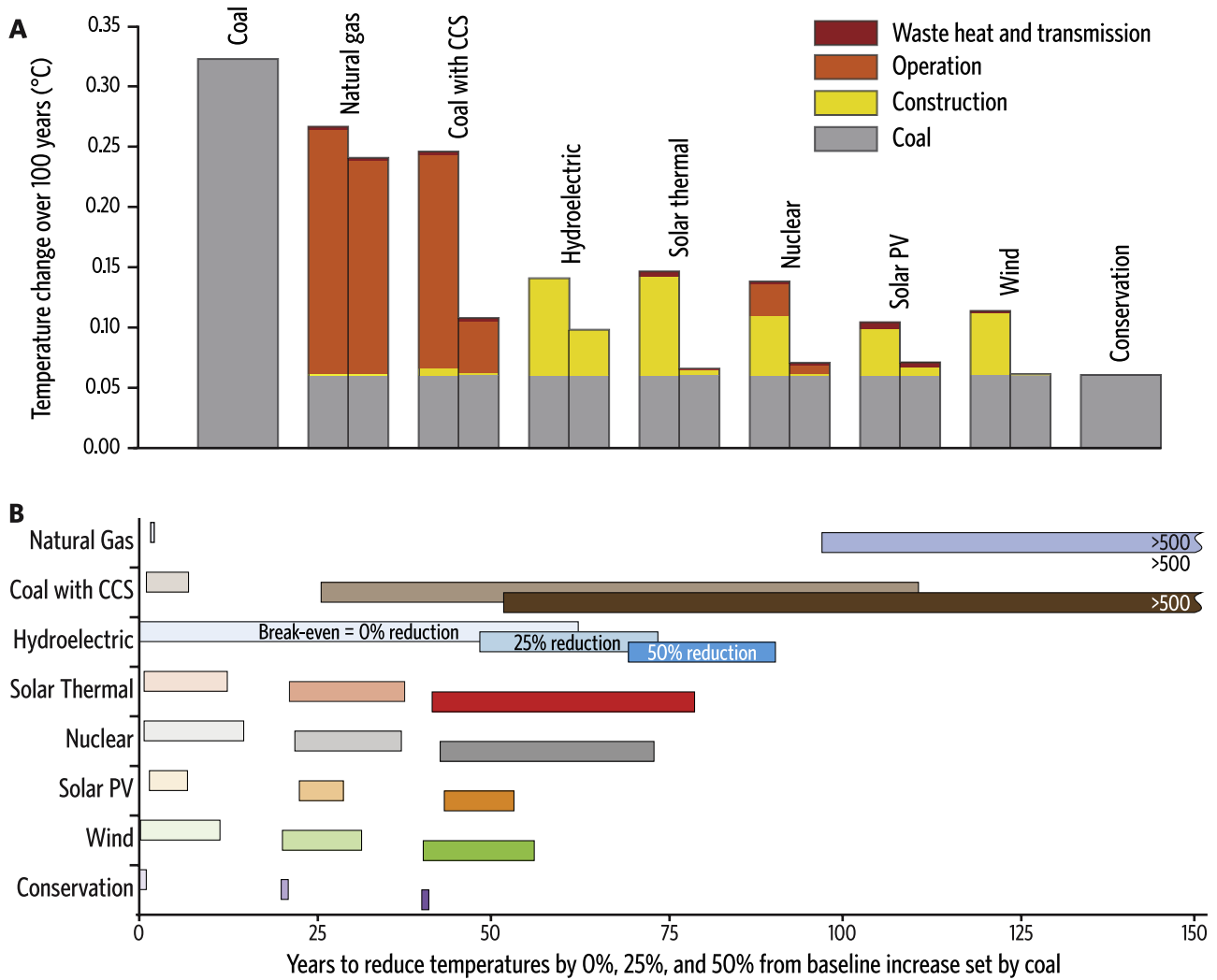
Figure 3. Transitions of 1 TW$_e$ of coal-based electricity generation to lower-emitting energy technologies produces modest reductions in the amount of global warming from GHG emissions; if the transition takes 40 yr to complete, only the lowest-emission technologies can offset more than half of the coal-induced warming in less than a century. (A) Increases in global mean surface temperature attributable to the 1 TW$_e$ energy system 100 yr after the start of a 40 yr transition to the alternative technology. Even if the coal-based system were phased out without being replaced by new power plants of any kind, GHGs released by the existing coal-fired plants during the phaseout would continue to add to global warming (rightmost column). Split columns reflect temperature changes calculated using both high and low emissions estimates from a range of life-cycle analyses, as described in the text and SOM text SN2 (available at stacks.iop.org/ERL/7/ 014019/mmedia). (B) Time required from the start of power generation by an alternative technology to achieve break-even, warming equal to what would have occurred without the transition from coal (lightest shading); a 25% reduction in warming (medium shading); and a reduction by half (darkest shading) as a result of the transition. The bars span the range between results derived using the lowest and highest LCA estimates of emissions. For numeric values, see SOM table S3 (available at stacks.iop.org/ERL/7/014019/mmedia).

had the transition not been undertaken, and that the transition would take 23–29 yr to produce a 25% reduction in HGE warming and 43–53 yr to avoid half of the HGE warming.

Natural gas plants emit about half the GHGs emitted by coal plants of the same capacity, yet a transition to natural gas would require a century or longer to attain even a 25% reduction in HGE warming (SOM table S3 available at stacks. iop.org/ERL/7/014019/mmedia). Natural gas substitution thus may not be as beneficial in the near or medium term as extrapolation from 'raw' annual GHG emissions might suggest.

Carbon capture and storage (CCS) also slows HGE warming only very gradually. Although CCS systems are estimated to have raw GHG emissions of ∼17%–∼27%

that of unmodified coal plants, replacement of a fleet of conventional coal plants by coal-fired CCS plants reduces HGE warming by 25% only after 26–110 yr. This transition delivers a 50% reduction in 52 years under optimistic assumptions and several centuries or more under pessimistic assumptions.

More generally, any electricity-generating technology that reduces GHG emissions versus coal plants by only a factor of two to five appears to require century-long times to accrue substantial temperature reductions. Comparison of 1 TW$_e$, 40 yr transitions from coal to a wide range of LGE energy technologies reveals little difference in warming produced by the various technologies until the transition is complete (figures 2(A)–(G)). Although it takes many decades
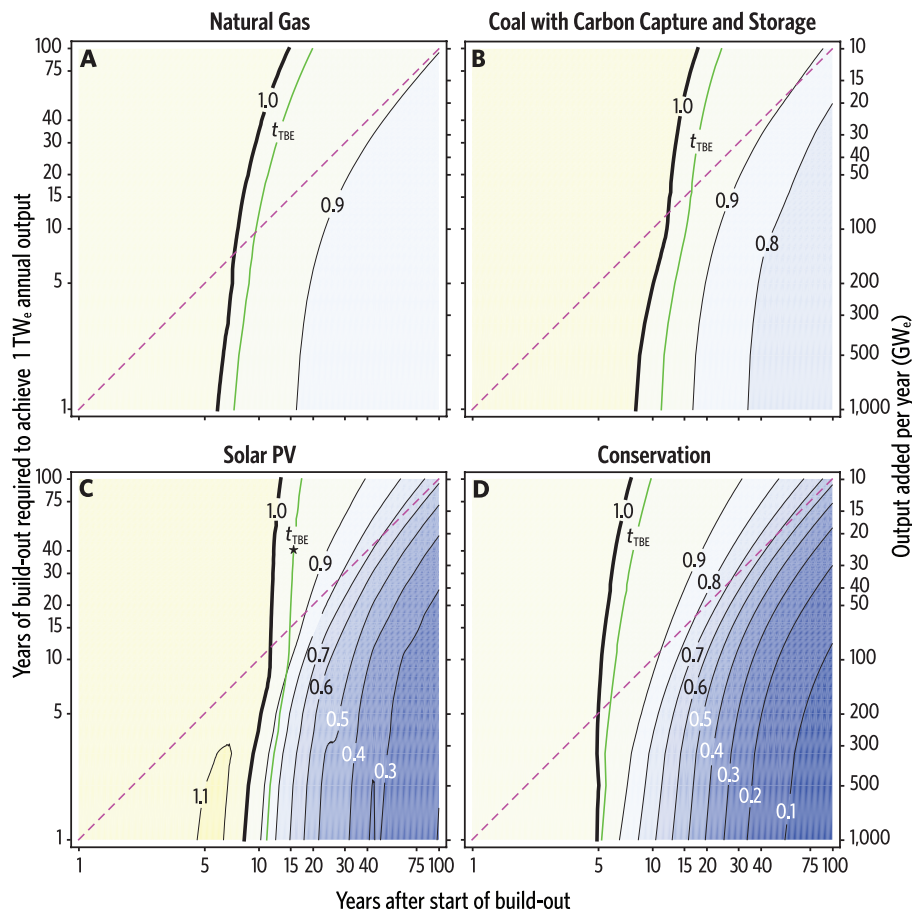
Figure 4. Analysis of a wide range of energy transition rates, scales, and technologies finds that replacement of coal-fired power plants requires many years to deliver climate benefits. For a given alternative energy technology and transition scale, the range of simulation results can be summarized by a contour plot; those above show results for 1 TW$_e$, linear transitions to (A) natural gas, (B) coal with CCS, (C) solar PV and (D) conservation; high emission estimates from LCA studies were used in each case. For plots of other technologies, transition scales, and build-out trajectories, see SOM figures S10 and S11 (available at stacks.iop.org/ERL/7/014019/mmedia). In these plots, the vertical axis represents the duration of the build-out; results span build-out durations from 1 to 100 yr, which corresponds to annual additions of output ranging from 10 to 1000 GW$_e$. Contour lines plot the ratio $\Delta T_{new}/\Delta T_{coal}$, where ΔT_{new} is the increase in global mean surface temperature projected to result from the transition to the lower-emission technology. Contour lines thus represent the time to achieve reductions in warming ranging from 10% (a ratio of 0.9) to 90% (a ratio of 0.1). Whereas the progress of the build-out (horizontal axis) is measured from the start of power generation in figure 3, here time is measured from the start of construction, which we assume lasts five years before each new plant begins generating. (For ease of comparison, conservation is treated similarly.) Dashed magenta lines indicate the completion of construction of the last plant in the build-outs. The instantaneous break-even point at which $\Delta T_{new} = \Delta T_{coal}$ is indicated by thick black curves. A better metric of the break-even time, however, is where the time-averaged integral of ΔT_{new} equals that of ΔT_{coal} (t_{TBE}, green curves). A 40 yr deployment of 1 TW$_e$ of solar PV, for example, would not reach t_{TBE} until year 15 of the build-out (asterisked point).

to achieve substantial benefits from a phaseout of coal-based power plants, instantaneously turning coal plants off without replacing the generating capacity would yield a 50% reduction in HGE warming in 11 yr, as shown in figure 4(D), which plots the reduction in temperature increases to be expected in any given year from elimination of 1 TW$_e$ of coal capacity by build-outs ranging in duration from 1 to 100 yr.

We selected coal-fired plants as the basis for comparison because this energy technology emits the most GHGs per unit electricity generated; replacing plants of this kind thus delivers the greatest climate benefits. If the new technology were instead to replace natural gas plants, then even less CO_2 emission would be avoided, and the times to achieve reductions in warming relative to a natural gas baseline would be even longer than projected here.

4. Effects of scale, duration, technological improvement and bootstrapping

Although we focus here on 40 yr, linear transitions of a 1 TW$_e$ energy system, we examined a far broader range of cases; none of these cases altered our central conclusions. Figure 4, for example, illustrates the HGE warming caused by transitions to several LGE energy technologies that range in duration from 1 to 100 yr. We have simulated transitions ranging from 0.1 to 10 TW$_e$. In addition to the linear transition presented here, we examined exponential and logistic transitions (SOM texts SD1–SD3 and figures S8, S11–S14 available at stacks.iop.org/ERL/7/014019/mmedia). We also analyzed plausible effects of technological improvement by reducing the emission per unit energy generation over time by

various exponential rates, an approach that effectively forces each technology under study to approach the zero emission case of conservation asymptotically (SOM text SD3 and figure S14 available at stacks.iop.org/ERL/7/014019/mmedia). The analysis reveals that the long timescale required for energy system transitions to reduce temperatures substantially is not sensitive to technological improvement. High rates of technological improvement could alter, however, the relative rank of energy technologies in their abilities to mitigate future warming.

Finally, we examined 'bootstrapping' transitions. The exponential, linear and logistic models all assume that generated electricity is used to displace coal and thus lower emissions. A very different strategy is to use a low-GHG-emitting technology to bootstrap itself. This strategy is particularly interesting for wind and solar PV because each of them require substantial amounts of electricity in the manufacturing of key components.

A bootstrapping transition uses electricity from the first plant built to manufacture more plants of the same kind, which in turn provide energy to build new plants, and so on exponentially (SOM text SD2 and figure S13 available at stacks.iop.org/ERL/7/014019/mmedia). In this approach, however, no electricity is turned over to the grid—and thus no coal is replaced—until the build-out goal has been installed and brought online, at which point the coal is displaced all at once. The effect of bootstrapping is thus equivalent to distributing the electrons from PV systems and using coal-generated electrons to construct the PV arrays.

Emissions estimates from the LCA studies we use in our principal analysis, in contrast, assume carbon intensities lower than that of coal-based electricity and thus lower emissions than would occur with either bootstrapping or coal as the source of energy for new plant construction. For both wind and solar, bootstrapping produces higher temperatures during the first 70–100 yr than would occur if the plants were constructed using power from the existing grid. For transitions lasting longer than 100 yr, bootstrapping does yield lower GHG emissions for plant construction and, eventually, lower temperatures than grid-connected build-outs. On this extended time scale, however, emissions for grid-connected models are likely to fall substantially as well, due to changes in the mix of electricity generation.

Figure 3(A) shows that, for fossil fuel plants, emissions from plant operation are the predominant source of life-cycle emissions, and they are responsible for the majority of the global temperature increase produced. Conservation yields the largest temperature reductions. In transitions to wind, solar, and nuclear technologies, temperature increases caused by emissions during plant construction exceed those due to plant operation; the resulting temperature increases are dwarfed, however, by those caused by emissions from coal plants as they are being phased out.

Temperature increases due to transmission and waste heat are small but can amount to a substantial fraction of the total temperature increase associated with the lowest emission technologies.

5. Sources of uncertainty

Our central result is that transitions from coal to energy technologies having lower carbon emissions will not substantially influence global climate until more than half a century passes, and that even large transitions are likely to produce modest reductions in future temperatures. These fundamental qualitative conclusions are robust, but our quantitative calculations incorporate important sources of uncertainty in representations of both the energy system and the physical climate system.

We characterize uncertainty in energy system properties by presenting both high and low estimates from life-cycle analyses (e.g., figures 1–3). Our model of the physical climate system is affected by uncertainties both in the relationship between greenhouse gas emissions and atmospheric concentrations and in the relationship between atmospheric concentrations and the resulting climate change. The IPCC [5] states that equilibrium climate sensitivity to a doubling of atmospheric CO_2 content 'is likely to lie between 2 and 4.5 °C with a most likely value of approximately 3 °C.' Our model yields a climate sensitivity of 3.18 °C per CO_2-doubling. Physical climate system uncertainties could thus potentially halve or double our quantitative results. The impact of most of these uncertainties would apply equally to all technologies, however, so relative amounts of warming resulting from different technology choices are likely to be insensitive to uncertainties about the climate system.

6. Conclusions

Here, we have examined energy system transitions on the scale of the existing electricity sector, which generates $\sim$1 TW_e primarily from approximately 3 TW thermal energy from fossil fuels [3]. It has been estimated, however, that 10–30 TW of carbon-neutral thermal energy must be provisioned by mid-century to meet global demand on a trajectory that stabilizes the climate with continued economic growth [1].

It appears that there is no quick fix; energy system transitions are intrinsically slow [13]. During a transition, energy is used both to create new infrastructure and to satisfy other energy demands, resulting in additional emissions. These emissions have a long legacy due to the long lifetime of CO_2 in the atmosphere and the thermal inertia of the oceans. Despite the lengthy time lags involved, delaying rollouts of low-carbon-emission energy technologies risks even greater environmental harm in the second half of this century and beyond. This underscores the urgency in developing realistic plans for the rapid deployment of the lowest-GHG-emission electricity generation technologies. Technologies that offer only modest reductions in emissions, such as natural gas and—if the highest estimates from the life-cycle analyses (SOM table S1 available at stacks.iop.org/ERL/7/014019/mmedia) are correct—carbon capture storage, cannot yield substantial temperature reductions this century. Achieving substantial reductions in temperatures relative to the coal-based system will take the better part of a century,

and will depend on rapid and massive deployment of some mix of conservation, wind, solar, and nuclear, and possibly carbon capture and storage.

Acknowledgments

References

[1] Hoffert M I *et al* 2002 Advanced technology paths to global climate stability: energy for a greenhouse planet *Science* **298** 981–7

[2] Pacala S and Socolow R 2004 Stabilization wedges: solving the climate problem for the next 50 years with current technologies *Science* **305** 968–72

[3] International Energy Agency 2010 *World Energy Outlook 2010* (Paris: OECD Publishing) (doi:10.1787/weo-2010-en)

[4] Friedlingstein P *et al* 2010 Update on CO_2 emissions *Nature Geosci.* **3** 811–2

[5] Forster P *et al* 2007 Changes in atmospheric constituents and radiative forcing *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 129–234

[6] Hansen J, Sato M and Ruedy R 1997 Radiative forcing and climate response *J. Geophys. Res.* **102** 6831–64

[7] Murphy D M, Solomon S, Portmann R W, Rosenlof K H, Forster P M and Wong T 1950 An observationally based energy balance for the Earth since *J. Geophys. Res.* **114** 1–14

[8] Hansen J, Lacis A, Rind D, Russell G, Stone P, Fung I, Ruedy R and Lerner J 1984 Climate sensitivity: analysis of feedback mechanisms *Climate Processes and Climate Sensitivity (AGU Geophysical Monograph Series 29)* ed J Hansen and T Takahashi (Washington, DC: American Geophysical Union) pp 130–63

[9] MacMynowski D G, Shin H-J and Caldeira K 2011 The frequency response of temperature and precipitation in a climate model *Geophys. Res. Lett.* **38** L16711

[10] Edenhofer O *et al* (ed) 2011 *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)

[11] Fearnside P M 2005 Greenhouse gas emissions from hydroelectric dams: reply to Rosa *et al Clim. Change* **75** 103–9

[12] Pacca S and Horvath A 2002 Greenhouse gas emissions from building and operating electric power plants in the Upper Colorado River Basin *Environ. Sci. Technol.* **36** 3194–200

[13] Smil V 2010 *Energy Transitions: History, Requirements, Prospects* (Santa Barbara, CA: ABC-CLIO)