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PERSPECTIVE

Rethinking wedges

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Abstract

Stabilizing CO_2 emissions at current levels for fifty years is not consistent with either an atmospheric CO_2 concentration below 500 ppm or global temperature increases below 2 °C. Accepting these targets, solving the climate problem requires that emissions peak and decline in the next few decades, and ultimately fall to near zero. Phasing out emissions over 50 years could be achieved by deploying on the order of 19 'wedges', each of which ramps up linearly over a period of 50 years to ultimately avoid 1 GtC y^{-1} of CO_2 emissions. But this level of mitigation will require affordable carbon-free energy systems to be deployed at the scale of tens of terawatts. Any hope for such fundamental and disruptive transformation of the global energy system depends upon coordinated efforts to innovate, plan, and deploy new transportation and energy systems that can provide affordable energy at this scale without emitting CO_2 to the atmosphere.

S Online supplementary data available from stacks.iop.org/ERL/8/011001/mmedia

1. Introduction

In 2004, Pacala and Socolow published a study in *Science* arguing that '[h]umanity can solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do' [1]. Specifically, they presented 15 options for 'stabilization wedges' that would grow linearly from zero to 1 Gt of carbon emissions avoided per year (GtC y^{-1}; 1 Gt $= 10^{12}$ kg) over 50 years. The solution to the carbon and climate problem, they asserted, was 'to deploy the technologies and/or lifestyle changes necessary to fill all seven wedges of the stabilization triangle'. They claimed this would offset the growth of emissions and put us on a trajectory to stabilize atmospheric CO_2 concentration at 500 ppm if emissions decreased sharply in the second half of the 21st century.

The wedge concept has proven popular as an analytical tool for considering the potential of different technologies to reduce CO_2 emissions. In the years since the paper was published, it has been cited more than 400 times, and stabilization wedges have become a ubiquitous unit in assessing different strategies to mitigate climate change (e.g. [2–5]). But the real and lasting potency of the wedge concept was in dividing the daunting problem of climate change into substantial but tractable portions of mitigation: Pacala and Socolow gave us a way to believe that the energy-carbon-climate problem was manageable.

An unfortunate consequence of their paper, however, was to make the solution seem easy (see, e.g. [6, 7]). And in the meantime, the problem has grown. Since 2004, annual emissions have increased and their growth rate has accelerated, so that more than seven wedges would now be necessary to stabilize emissions and—more importantly—stabilizing emissions at current levels for 50 years does not appear compatible with Pacala and Socolow's target of an atmospheric CO_2 concentration below 500 ppm nor the international community's goal of limiting the increase in global mean temperature to 2 °C more than the pre-industrial era.

Here, we aim to revitalize the wedge concept by redefining what it means to 'solve the carbon and climate problem for the next 50 years'. This redefinition makes clear both the scale and urgency of innovating and deploying carbon-emissions-free energy technologies.

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2. Solving the climate problem

Stabilizing global climate requires decreasing CO_2 emissions to near zero [8–11]. If emissions were to stop completely, global temperatures would quickly stabilize and decrease gradually over time [8, 12, 13]. But socioeconomic demands and dependence on fossil-fuel energy effectively commit us to many billions of tons of CO_2 emissions [14], and at the timescale of centuries, each CO_2 emission to the atmosphere contributes another increment to global warming: peak warming is proportional to cumulative CO_2 emissions [15, 16]. Cumulative emissions, in turn, integrate all past emissions as well as those occurring during three distinct phases of mitigation: (1) slowing growth of emissions, (2) stopping growth of emissions, and (3) reducing emissions. Although they noted that stabilizing the climate would require emissions to 'eventually drop to zero', Pacala and Socolow nonetheless defined 'solv[ing] the carbon and climate problem over the next half-century' as merely stopping the growth of emissions (phases 1 and 2). Further reductions (phase 3), they said, could wait 50 years if the level of emissions were held constant in the meantime.

But growth of emissions has not stopped (phase 2) or even slowed (phase 1), it has accelerated [17, 18]. In 2010, annual CO_2 emissions crested 9 GtC. At this level, holding emissions constant for 50 years (phase 2) is unlikely to be sufficient to avoid the benchmark targets of 500 ppm or 2 °C.

To support this assertion, we performed ensemble simulations using the UK Met Office coupled climate/carbon cycle model, HadCM3L (see supplementary material available at stacks.iop.org/ERL/8/011001/mmedia), to project changes in atmospheric CO_2 and global mean temperature in response to emissions scenarios in which seven wedges (W7) and nine wedges (W9) were immediately subtracted from the A2 marker scenario of the Intergovernmental Panel on Climate Change (IPCC)'s Special Report on Emissions Scenarios (SRES) [19] beginning in 2010 (figure 1). In the first half of this century, the A2 scenario is near the center of the plume of variation of the SRES emissions scenarios [20]. Indeed, actual annual emissions have exceeded A2 projections for more than a decade [21, 22]. During this period, strong growth of global emissions has been driven by the rapid, carbon-intensive growth of emerging economies [23, 24], which has continued despite the global financial crisis of 2008–9 [18]. For these reasons we believe that, among the SRES scenarios, A2 represents a reasonable 'business-as-usual' scenario. However, if emissions were to suddenly decline and follow a lower emissions business-as-usual trajectory such as B2, fewer wedges would be necessary to stabilize emissions, and deployment of seven wedges would reduce annual emissions to 4.5 GtC in 2060. Thus, mitigation effort (wedges) required to stabilize emissions is dependent on the choice of baseline scenario, but a half-century of emissions at the current level will have the same effect on atmospheric CO_2 and the climate regardless of what scenario is chosen.

We also note that the climate model we used, HadCM3L, has a strong positive climate/carbon cycle feedback mainly associated with the dieback of the Amazon rainforest [25]. As a result, HadCM3L projected the highest level of atmospheric CO_2 concentrations among eleven Earth system models that were driven by a certain CO_2 emission scenario [26]. However, this strong positive climate/carbon cycle feedback operates in simulations of both the A2 and wedge (W7 and W9) scenarios. Therefore, the relative effect of wedges, as opposed to the absolute values of projected atmospheric CO_2 and temperature, is expected to be less dependent on the strength of climate/carbon cycle feedback.

Atmospheric CO_2 concentration and mean surface temperatures continue to rise under the modeled W7 scenario (figures 1(A)–(C)). Deploying 7 wedges does not alter projected mean surface temperatures by a statistically significant increment until 2046 ($\alpha = 0.05$ level), at which time the predicted difference between mean temperatures in the A2 and W7 scenarios is 0.14 ± 0.08 °C. In 2060, the difference in projected mean temperatures under the two scenarios is 0.47 ± 0.07 °C. Further, under the W7 scenario, our results indicate atmospheric CO_2 levels will exceed 500 ppm in 2042 (reaching 567 ± 1 ppm in 2060) (figure 1(B)), and 2 °C of warming in 2052 (figure 1(C)). Immediately stabilizing global emissions at 2010 levels ($\sim$10.0 GtCy^{-1}), which would require approximately nine wedges (thus W9) under the A2 scenario, has a similarly

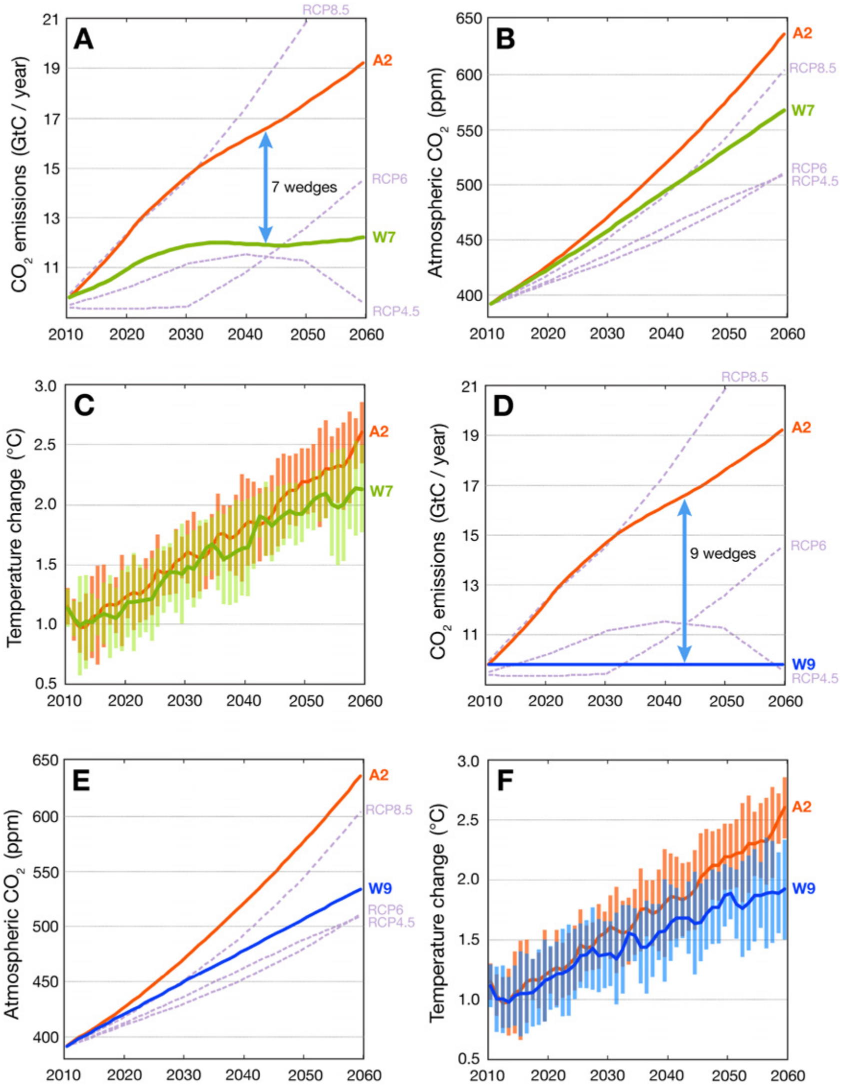

Figure 1. Modeled effects of deploying wedges. (A) Future CO_2 emissions under SRES A2 marker scenario and the A2 scenario reduced by deployment of 7 wedges (W7). The response of (B) atmospheric CO_2 and (C) global mean surface temperature under W7. (D) Future CO_2 emissions under SRES A2 marker scenario and stabilized at 2010 levels (reduced by approximately 9 wedges relative to the A2 scenario) (W9). The response of (E) atmospheric CO_2 and (F) global mean surface temperature under W9. Error bars in ((C) and (F)) are 2-sigma. Dashed lines in (A), (B), (D) and (E) show emissions and concentrations of representative concentration pathways RCP4.5, RCP6, and RCP8.5 [38]. Mean temperatures reflect warming relative to the pre-industrial era.

modest effect on global mean surface temperatures and atmospheric CO_2, with warming of 1.92 ± 0.4 °C in 2060 and atmospheric CO_2 exceeding 500 ppm by 2049 (figures 1(D)–(F)). Our projections therefore indicate that holding emissions constant at current levels for the next half-century would cause substantial warming, approaching or surpassing current benchmarks [27–29] even before any reduction of emissions (phase 3) begins.

Insofar as current climate targets accurately reflect the social acceptance of climate change impacts, then, solving the carbon and climate problem means not just stabilizing but sharply reducing CO_2 emissions over the next 50 years.

We are not alone in drawing this conclusion (see, e.g. [30–32]). For example, at least some integrated assessment models have now found that the emissions reductions required to prevent atmospheric CO_2 concentration from exceeding 450 ppm are no longer either physically or economically feasible [11, 33, 34], and that preventing CO_2 concentration from exceeding 550 ppm will also be difficult if participation of key

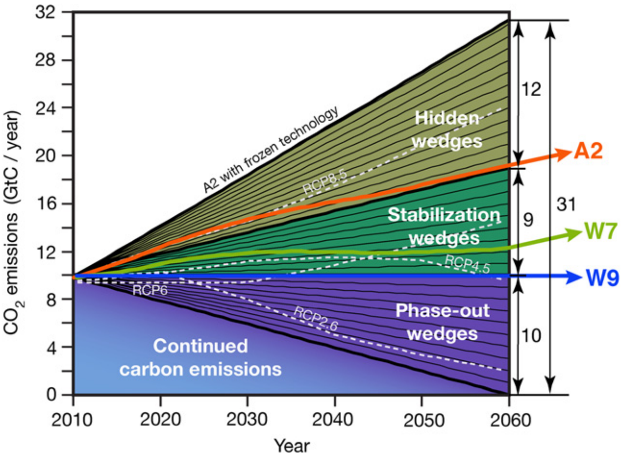

Figure 2. Idealization of future CO$_2$ emissions under the business-as-usual SRES A2 marker scenario. Future emissions are divided into *hidden* (sometimes called 'virtual') wedges (brown) of emissions avoided by expected decreases in the carbon intensity of GDP by ~1% per year, *stabilization* wedges (green) of emissions avoided through mitigation efforts that hold emissions constant at 9.8 GtC y^{-1} beginning in 2010, phase-out wedges (purple) of emissions avoided through complete transition of technologies and practices that emit CO$_2$ to the atmosphere to ones that do not, and allowed emissions (blue). Wedges expand linearly from 0 to 1 GtC y^{-1} from 2010 to 2060. The total avoided emissions per wedge is 25 GtC, such that altogether the hidden, stabilization and phase-out wedges represent 775 GtC of cumulative emissions.

countries such as China and Russia is delayed [11]. Most model scenarios that allow CO$_2$ concentrations to stabilize at 450 ppm entail negative carbon emissions, for example by capturing and storing emissions from bioenergy [11].

A different body of literature has concluded that cumulative emissions of 1 trillion tons of carbon (i.e. 1000 GtC) are likely to result in warming of 2 °C [15, 35]. Whereas Pacala and Socolow's original proposal implied roughly 944 GtC of cumulative emissions (305 GtC prior to 2004, 389 GtC between 2004 and 2054, and another 250 GtC between 2054 and 2104 if emissions decrease at 2% y^{-1} as they suggested), stabilizing emissions at 2010 levels for 50 y and decreasing at 2% y^{-1} afterward increases the cumulative total to 1180 GtC of emissions (356 GtC prior to 2010, 491 GtC between 2010 and 2060, and 336 GtC between 2060 and 2110 at which time annual emissions remain at nearly 3.2 GtC y^{-1}). Lastly, we note that even though emissions in the lowest of the new representative concentration pathways (RCP2.6) peak in 2020 at just 10.3 GtC y^{-1} and decline sharply to only 2.0 GtC y^{-1} in 2060 (figure 2), the concentration of atmospheric CO$_2$ nonetheless reaches 443 ppm in 2050 [36–38]. In contrast, emissions of the intermediate pathway RCP4.5 rise modestly to 11.5 GtC y^{-1} in 2040 before declining to 9.6 GtC y^{-1} in 2060, which leads to atmospheric CO$_2$ concentrations of 509 ppm in 2060 on the way to 540 ppm in 2100. These pathways, along with the integrated assessment models and cumulative emissions simulations all support our finding that 50 y of current emissions is not a solution to climate change.

Unless current climate targets are sacrificed, solving the climate problem requires significantly reducing emissions over the next 50 years. Just how significant those reductions need to be will depend on a global trade-off between the damages imposed by climatic changes and the costs of avoiding them. But given substantial uncertainties associated with climate model projections (e.g., climate sensitivity), the arbitrary nature of targets like 500 ppm and 2 °C, and the permanence implied by the term 'solution', the ultimate solution to the climate problem is a complete phase-out of carbon emissions.

3. Counting wedges

But significantly reducing current emissions while also sustaining historical growth rates of the global economy is likely to require many more than seven wedges. Gross world product (GWP) projections embedded in the A2 scenario imply as many as 31 wedges would be required to completely phase-out emissions, grouped into three distinct groups:

(1) 12 'hidden' wedges that represent the continued decarbonization of our energy system at historical rates (i.e. decreases in the carbon intensity of the global economy that are assumed to regardless of any additional efforts to mitigate emissions) [9, 39].
(2) 9 'stabilization' wedges that represent additional efforts to mitigate emissions above and beyond the technological progress already assumed by the scenario [1]. And (3), 10 'phase-out' wedges that represent the complete transition from energy infrastructure and land-use practices that emit CO_2 (on net) to the atmosphere to infrastructure and practices which do not (figure 2) [9, 14, 40].

There is good reason to be concerned that at least some number of the hidden wedges will not come to be—that the rates of decarbonization assumed by almost all scenarios of future emissions may underestimate the extent to which rising energy demand will be met by increased use of coal and unconventional fossil fuels [24, 41]. Moreover, there is no way to know whether a wedge created by deploying carbon-free energy technology represents additional mitigation effort (i.e. a stabilization wedge) or something that would have happened in the course of normal technological progress (i.e. a hidden wedge). Thus, in assessing the efficacy of efforts to reduce emissions, it may be more useful to tabulate wedges based only on the current carbon intensity of global energy and food production and projected demand for energy and food, without reference to any particular technology scenario. Doing so would clarify the full level of decarbonization necessary and remove the question of whether emissions reductions that do occur should count as mitigation or not. But even assuming that historical rates of decarbonization will persist and therefore that many hidden wedges will materialize, phasing-out emissions altogether will entail nearly three times the number of additional wedges that Pacala and Socolow originally proposed—a total of 19 wedges under the A2 scenario (figure 2).

4. The urgent need for innovation

Confronting the need for as many as 31 wedges (12 hidden, 9 stabilization and 10 phase-out), the question is whether there are enough affordable mitigation options available, and—because the main source of CO_2 emissions is the burning of fossil fuels—the answer depends upon an assessment of carbon-free energy technologies. There is a longstanding disagreement in the literature between those who argue that existing technologies, improved incrementally, are all that is needed to solve the climate problem (e.g. [1]) and others who argue that more transformational change is necessary (e.g. [42]). Although the disagreement has turned on the definitions of incremental and transformative and the trade-offs of a near-term versus a longer-term focus, the root difference lies in the perceived urgency of the climate problem [6]. The emission reductions required by current targets, let alone a complete phase-out of emissions, demand fundamental, disruptive changes in the global energy system over the next 50 years. Depending on what sort of fossil-fuel infrastructure is replaced and neglecting any emissions produced to build and maintain the new infrastructure (see, e.g. [43]), a single wedge represents 0.7–1.4 terawatts (TW) of carbon-free energy (or an equivalent decrease in demand for fossil energy). Whether the changes to the energy system are called incremental or revolutionary, few would dispute that extensive innovation of technologies will be necessary to afford many terawatts of carbon-free energy and reductions in energy demand [42, 44, 45].

Currently, only a few classes of technologies might conceivably provide carbon-free power at the scale of multiple terawatts, among them fossil fuels with carbon capture and storage (CCS), nuclear, and renewables (principally solar and wind, and perhaps biomass) [42, 46, 47]. However, CCS has not yet been commercially deployed at any centralized power plant; the existing nuclear industry, based on reactor designs more than a half-century old and facing renewed public concerns of safety, is in a period of retrenchment, not expansion; and existing solar, wind, biomass, and energy storage systems are not yet mature enough to provide affordable baseload power at terawatt scale. Each of these technologies must be further developed if they are to be deployed at scale and at costs competitive with fossil energy.

Yet because investments in the energy sector tend to be capital intensive and long term, research successes are often not fully appropriable [48], and technologies compete almost entirely on the price of delivered electricity, private firms tend to underinvest in R&D, which has made energy one of the least innovative industry sectors in modern economies [44]. Supporting deployment of newer energy technologies at large scales will undoubtedly lead to further development and reduced costs [45, 49, 50], but additional public support for early stage R&D will also be necessary to induce needed innovation [6, 44, 45, 51–53]. Moreover, it is imperative that policies and programs also address the intermediate stages of development, demonstration, and commercialization, when ideas born of public-funded research must be transferred to and diffused among private industries [44, 54, 55].

5. Conclusions

In 2004, Pacala and Socolow concluded that 'the choice today is between action and delay'. After eight years of mostly delay, the action now required is significantly greater. Current climate targets of 500 ppm and 2 °C of warming will require emissions to peak and decline in the next few decades. Solving the climate problem ultimately requires near-zero emissions. Given the current emissions trajectory, eliminating emissions over 50 years would require 19 wedges: 9 to stabilize emissions and an additional 10 to completely phase-out emissions. And if historical, background rates of decarbonization falter, 12 'hidden' wedges will also be necessary, bringing the total to a staggering 31 wedges.

Filling this many wedges while sustaining global economic growth would mean deploying tens of terawatts of carbon-free energy in the next few decades. Doing so would entail a fundamental and disruptive overhaul of the global energy system, as the global energy infrastructure is replaced with new infrastructure that provides equivalent amounts of energy but does not emit CO_2. Current technologies and systems cannot provide the amounts of carbon-free energy needed soon enough or affordably enough to achieve this transformation. An integrated and aggressive set of policies and programs is urgently needed to support energy technology innovation across all stages of research, development, demonstration, and commercialization. No matter the number required, wedges can still simplify and quantify the challenge. But the problem was never easy.

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