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Stabilisation wedges: measuring progress towards transforming
the global energy and land use systemsNathan Johnson^{*} , Robert Gross and Iain Staffell

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^{*} Author to whom any correspondence should be addressed.E-mail: nathan.johnson17@imperial.ac.uk**Keywords:** climate change, mitigation, decarbonisation, energy systems, land use change, climate change communication, public engagementSupplementary material for this article is available [online](#)

Abstract

Fifteen years ago, Pacala and Socolow argued that global carbon emissions could be stabilised by mid-century using a portfolio of existing mitigation strategies. We assess historic progress for each of their proposed mitigation strategies and convert this into the unit of ‘wedges’. We show that the world is on track to achieve 1.5 ± 0.9 wedges relative to seven required to stabilise emissions, or 14 required to achieve net-zero emissions by mid-century. Substantial progress has been made in some domains that are not widely recognised (improving vehicle efficiency and declining vehicle use); yet this is tempered by negligible or even negative progress in many others (particularly tropical tree cover loss in Asia and Africa). By representing global decarbonisation efforts using the conceptually simple unit of wedges, this study helps a broader audience to understand progress to date and engage with the need for much greater effort over the coming decades.

1. Introduction

Climate strikes led by Greta Thunberg became a global movement in a matter of months and the protests of Extinction Rebellion have spread across the globe. The UNFCCC Paris Agreement [1] has cemented commitments to limiting global warming and reducing carbon emissions onto the international agenda. And yet, political inaction and low public engagement remain substantial barriers to effectively mitigating climate change [2–5]. The resistance to change that characterises those less engaged with climate change has been attributed to feelings of helplessness that stem from intellectual overload, the sheer size of the problem and perceptions of intractability [4–8]. If the necessary global response to climate change could be divided into smaller (albeit still substantial) solutions and communicated in simple terms to a broad audience, routes to mitigating climate change might appear more tangible and obtainable [4, 9, 10]. If converted into targets, these part solutions could be used to benchmark progress to date. This would inform the same broad audience as to how individual and national actions have contributed towards the necessary transition and the scale

of the challenge that lies ahead. There are now over 5 million electric vehicles on the road and wind farms generate over 1 PWh of electricity each year [11], but how much do these actions actually contribute towards meeting global targets for decarbonisation?

Typically, researchers have investigated the relationship between technology, society and carbon emissions using contrasting approaches: Kaya decompositions [12] and integrated assessments [13]. While Kaya provides simple communications, its level of abstraction—limited to population, income per capita, the energy intensity of the economy and the carbon intensity of energy provision—gives no insight about which aspects of technology and society are helping or hindering global decarbonisation efforts. In contrast, integrated assessments provide detailed sectoral pathways for the necessary transformation but lack the conceptual simplicity to resonate with a wider audience. Despite their complexity, integrated assessments are a substantial part of energy and climate research [13, 14]; however, there is a dearth of studies which compare their technological and societal roadmaps to historical progress in the global energy and land use systems.

The IEA Tracking Clean Energy Progress (TCEP) [11] project formulates pathways for technology uptake consistent with 2 °C of warming. When compared against historical progress, just seven of 45 technologies are on-track. While useful for benchmarking historical energy system changes, TCEP has not transcended complexity: it uses sector-specific units to report progress (e.g. TWh and mpg), and crucially it does not explicitly tie changes in the energy system to carbon emissions. The cause-and-effect relationship between actions and emissions is instrumental in motivating the public and policy makers to act [4, 6, 7]. It informs them as to how their decisions have contributed towards meeting global climate targets, which is essential for improving the tractability of the climate problem and building support for more stringent climate policies [4, 6, 7].

2. Background

Fifteen years ago, Pacala and Socolow [15] wrote their seminal paper that presented a simple and intuitive way to disaggregate and visualise the mitigation efforts required to stem rising global temperatures. The simplicity and flexibility of their analysis resonated with a very broad audience, as evidenced by its widespread use in education [16]. The paper contrasted two idealised 50 year futures: business as usual (BAU) and stabilisation (figure 1).

No single technology could feasibly halve global carbon emissions within 50 years, so the emissions gap between BAU and stabilisation was divided into seven ‘stabilisation wedges’. Each wedge represents an activity that reduces carbon emissions to the atmosphere, starting from zero in 2004 and increasing linearly to 1 billion tonnes (GtC) yr⁻¹ of avoided BAU carbon emissions in 2054. For Pacala and Socolow, ‘solving the carbon and climate problem over the next fifty years’ meant introducing strategies to ‘fill’ all seven wedges (table 1).

The wedge framework has become a popular tool for analysing and communicating carbon mitigation potentials [18–20]. It has not gone without criticism, primarily for being simplistic, under-ambitious, and focusing on a narrow subset of technologies [21–23]; however, it remains a useful framework to build upon. A quarter of the wedges’ 50 year timeline has now elapsed, which serves as a useful point to reflect on global progress. In this paper, we quantify the emissions mitigated by each strategy listed in table 1 between 2004 and 2017 and compare this to the mitigation required to achieve a wedge.

Despite its usefulness as an analytical and communicational tool, several studies have challenged the wedge framework. With zero technological or behavioural progress, emissions would increase faster than they do under BAU [24]; therefore, embedded in BAU are many activities similar to those captured by the stabilisation wedges. ‘Virtual wedges’ represent

carbon emissions reductions that occur in the BAU scenario relative to a virtual reference scenario in which emissions increase in proportion with economic activity [24]. Virtual wedges cannot contribute towards filling the stabilisation triangle because their ‘efforts’ have already been expended in preventing BAU emissions from growing more quickly. In one decomposition analysis [25], it was shown that the vast majority of virtual wedges are likely to be achieved via energy intensity improvements, primarily arising from structural shifts in the economy toward more energy efficient sectors. However, with assumptions of falling capital costs and rising fuel prices, mitigation options like solar and wind energy may also contribute virtual wedges [25–27].

The assumptions made in the original wedge framework may underestimate the additional mitigation effort required to limit warming to 2 °C. Two studies have modelled the effect of deploying different numbers of stabilisation wedges on atmospheric CO₂ concentrations and global surface temperatures [21, 22]. By extrapolating recent emissions growth, these studies found that 7–9 wedges would be required to stabilise emissions between 2010 and 2060; however, warming would approach or exceed 2 °C even before emissions had subsequently started to fall. They proposed that limiting warming to 2 °C would require an additional 7–10 ‘phase-out’ wedges—which represent the effort required to drive emissions from the stabilisation trajectory towards net-zero. Though authors may disagree on the number of wedges required to limit warming to 2 °C (from 14 to 19) [21, 22], the consensus is clear in one respect: many more than seven wedges must be deployed over the next 50 years to ‘solve the climate problem’.

The original wedge strategies cover many key mitigation options, but they were not intended to be an exhaustive list and thus they contain several gaps. Firstly, the original list of strategies did not cover all sources and sinks of emissions, with consumption patterns (e.g. diet and recycling) notably receiving almost no attention. Secondly, the original strategies focused explicitly on technologies that were existing at the time of publication, technical progress means that more mitigation options are now available. For example, the IPCC [28] stress the importance of negative emissions technologies in offsetting ‘residual’ emissions from sectors that are more difficult to decarbonise (e.g. cement production and aviation). Thirdly, some of the original strategies might now be considered incompatible with aspirations to limit warming to 2 °C. No matter how rapidly the efficiency of coal-fired power stations increases (strategy 4), generating twice as much electricity from unabated coal in 2054 will not limit warming to 2 °C. Finally, the original wedge framework focused exclusively on technologies capable of reducing BAU emissions. Not included in Pacala and Socolow’s BAU scenario are unforeseen negative developments which

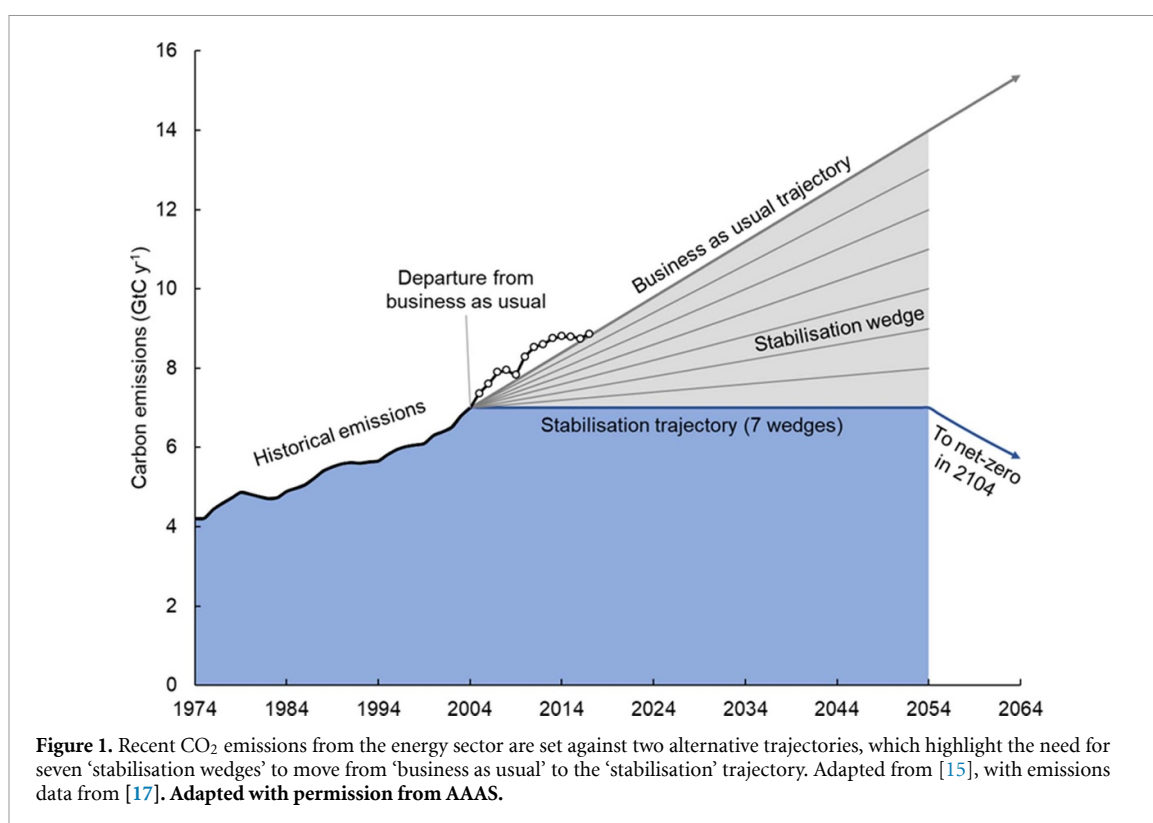


Table 1. Sixteen mitigation options that could fill a wedge between 2004 and 2054. From [15]. Adapted with permission from AAAS.

Strategy	Effort required in 2054 to achieve one wedge
1. Efficient cars	Increase fuel economy for 2 billion cars from 30 to 60 US mpg (12.8–25.5 km l ⁻¹)
2. Reduced use of cars	Decrease car travel for 2 billion 30 mpg cars from 10 000–5000 miles yr ⁻¹ (16 100–8050 km yr ⁻¹)
3. Efficient buildings	Cut carbon emissions by one-quarter in buildings and appliances projected for 2054
4. Efficient coal plants	Produce twice the 2004 coal power output at 60% instead of 40% efficiency (compared with 32% in 2004)
5. Coal-to-gas fuel-switching	Replace 10 800 TWh of generation from 50% efficient coal plants with equivalent generation from 60% efficient gas plants
6. CO ₂ capture and storage (CCS) at baseload power plant	Introduce CCS at 800 GW of coal plants or 1600 GW of natural gas plants
7. CCS at H ₂ production plant	Introduce CCS at plants producing 250 MtH ₂ yr ⁻¹ from coal or 500 MtH ₂ yr ⁻¹ from gas
8. CCS at coal-to-synfuels plant	Introduce CCS at coal-to-synfuels plants producing 30 million barrels (4.1 million tonnes) d ⁻¹ , if half of the feedstock carbon is available for capture
9. Nuclear power for coal power	Replace 5400 TWh of generation from 50% efficient coal plants with equivalent generation from nuclear
10. Wind power for coal power	Replace 5400 TWh of generation from 50% efficient coal plants with equivalent generation from wind
11. Solar photovoltaic (PV) power for coal power	Replace 5400 TWh of generation from 50% efficient coal plants with equivalent generation from solar PV
12. Hydrogen and electric vehicles	Replace 2 billion 60 mpg cars with hydrogen or electric vehicles, provided they run on zero carbon fuel
13. Ethanol for gasoline	Produce 28 million barrels (3.5 million tonnes) of ethanol per day to displace gasoline, provided the ethanol is fossil-carbon free
14. Reduced deforestation and plantations	Decrease tropical deforestation emissions to zero instead of 0.5 GtC yr ⁻¹ and establish 300 Mha of new tree plantations
15. Afforestation and reforestation	Afforest or reforest 250 Mha of forest in the tropics and 417 Mha in the temperate zone
16. Conservation agriculture	Apply to all cropland

would raise emissions beyond BAU [23]. These so-called threat wedges include rapid growth in demand for cheap fossil energy in developing countries, fugitive methane emissions from hydraulic fracturing (fracking) of shale gas formations, and extraction of heavy oils from tar sands [23]. From a mitigation perspective, preventing a threat wedge from materialising ought to be considered equal to achieving a stabilisation wedge, as both prevent 1 GtC entering the atmosphere in 2054.

Overall, these studies highlight that after 15 years of muted action, the decarbonisation challenge is far greater than was anticipated by Pacala and Socolow. Between 2004 and 2017, emissions grew faster on average than they did in the 30 years prior, thus the global effort to curtail emissions was expended on preventing BAU emissions from growing more quickly. Extrapolating recent emissions growth highlights that a greater number of wedges (7–9) are now required to stabilise emissions, and yet more wedges (14–19) are required to limit warming to 2 °C.

3. Methods

The following sections discuss general aspects of the methods: the calculation of the effort required to achieve a wedge and progress to date, the two scenarios we consider, and general limitations of the methods. The full calculations, data sources and specific limitations relating to our assessment of each mitigation strategy are provided in section 1 of the SI (available online at stacks.iop.org/ERL/16/064011/mmedia).

3.1. Calculating required effort and progress to date

We calculate progress for each mitigation strategy using simple, strategy-specific calculations adapted from Pacala and Socolow [15]. To be ‘on track’ to achieving a wedge in 2054, in 2017 a strategy should have reduced carbon emissions by 0.26 GtC yr⁻¹ relative to the BAU scenario, and from 2004 to 2017 cumulative emissions reductions should total 1.69 GtC. Not being ‘on track’ does not mean that a strategy has ‘failed’ per se. Pacala and Socolow proposed more strategies than wedges needed to be filled (16 vs 7), and some strategies (e.g. solar power and electric vehicles) are expected to follow sigmoid adoption curves and would therefore lag in the early years compared with the linear adoption rates assumed by wedges (e.g. a step change from 3 to 110 GW of new solar generation built per year in 2004) [29]. Rather, being ‘on track’ indicates the pace of adoption required for a mitigation strategy to have a materially significant impact on carbon emissions over the course of 50 years.

Each mitigation strategy is defined by four features which are listed in table 2 and illustrated using the vehicle efficiency strategy. With this example, fuel

economy should have increased from 30 to 41 US mpg (12.8–17.4 km l⁻¹) between 2004 and 2017—a 37% increase. The relative increase in fuel economy is fastest at the beginning of the 50 year period because improvements in fuel economy are reflected across a smaller fleet of cars.

When calculating the emissions mitigated by a strategy, the features of each wedge strategy give rise to three potential issues which affect the effort required to achieve a wedge. Firstly, the value for the primary variable cited by Pacala and Socolow could be contradicted by more recent sources. For example, if global average fuel economy in 2004 was lower than assumed, the improvement in fuel economy required to achieve a wedge is commensurately lower as each car burns more fuel. Secondly, Pacala and Socolow’s secondary assumptions may be contradicted by more recent sources. For example, if there are a greater number of cars on the road or each car travels further than was anticipated, fuel economy must improve by a smaller amount to achieve a wedge as each unit improvement in fuel economy is reflected across a greater number of vehicle miles. Finally, the change in the primary variable that Pacala and Socolow assumed would occur under BAU could be contested. For example, if fuel economy improves by 50% under BAU, rather than remaining constant, a greater improvement is required as BAU cars have lower emissions and so each unit of improvement contributes a smaller emissions saving. To combat these potential shortcomings, we calculated progress using two different scenarios.

3.2. Rounded and recalculated scenarios

The *rounded* scenario is idealistic and carries forward all Pacala and Socolow’s assumptions, including the starting assumption for each primary variable in 2004. The only information drawn from new sources was the observed relative change in the primary variable, which was applied to Pacala and Socolow’s starting assumption to judge progress towards achieving a wedge. Though not an accurate exercise in carbon accounting, the *rounded* scenario can easily be related back to Pacala and Socolow’s original targets and is better aligned with their conceptually simple way of perceiving energy system change. Continuing the example of vehicle efficiency, we estimate that global average fuel economy improved by approximately 22% between 2004 and 2017 [30]. Over the same period, the vehicle efficiency wedge required an improvement of 37% and so historic progress is on track for 0.60 wedges.

The *recalculated* scenario provides a comprehensive, updated estimate of the progress made towards achieving a wedge. We calculated progress based on the absolute change in the primary variable reported by recent sources. Secondary underpinning assumptions were also updated with estimates from the literature. In many cases, these

Table 2. The four features of a wedge strategy exemplified using the vehicle efficiency strategy.

Feature	Worked example
1. Primary variable in 2004	The global average fuel economy of cars is 30 US mpg (12.8 km l^{-1})
2. Change in primary variable under BAU	Fuel economy does not improve between 2004 and 2054
3. Secondary underpinning assumptions	The carbon content of gasoline is $3 \text{ kg US gallon}^{-1}$ (0.79 kg l^{-1}) The number of cars on the road increases linearly from 600 million in 2004 to 2 billion in 2054 The average miles travelled per car is $10\,000 \text{ miles yr}^{-1}$ ($16\,100 \text{ km yr}^{-1}$) and does not change
4. The effort required to achieve a wedge in 2054	Fuel economy must double from 30 mpg in 2004 to 60 mpg in 2054 ($12.8\text{--}25.5 \text{ km l}^{-1}$)

estimates were uncertain. Where possible, uncertainties were propagated using Monte Carlo simulations (see section 1.1 of the SI). The mitigation effort required to achieve a wedge was then recalculated to preserve the 0.26 GtC yr^{-1} emissions reduction in 2017 and the 1.69 GtC cumulative saving between 2004 and 2017. Returning to the vehicle efficiency example, we estimate that in 2004 the average fuel economy of conventional cars was 23.7 ± 0.8 US mpg ($10.1 \pm 0.3 \text{ km l}^{-1}$) [30], and so fuel economy needed to improve by fewer units than was anticipated in the *rounded* scenario. There were also approximately 4% more cars on the road travelling on average 27% further than was anticipated [31, 32], thus the emissions saved per unit improvement in fuel economy is greater in the *recalculated* scenario than in the *rounded* scenario. As a result, fuel economy needed to improve by just 19% in the *recalculated* scenario (relative to 37% in the *rounded* scenario) and so historic progress is on track to achieve 1.00 ± 0.07 wedges.

3.3. Methodological limitations

A noticeable omission from both our *rounded* and *recalculated* scenarios is the consideration of different BAU cases for each strategy. We opted to leave the original BAU assumptions from Pacala and Socolow unchanged for two reasons. Firstly, while there may be good grounds to dispute the BAU cases assumed for each strategy, the same could be said of alternative BAU scenarios, as the nature of determining future energy and land use systems is inherently uncertain. Secondly, although the consideration of multiple different BAU cases may provide a more robust estimate of emissions savings, it must be remembered that one of the main objectives of this paper—to reduce the complexity and improve the tractability of the climate problem—is achieved in part by judging progress against a single, simple BAU scenario.

A key limitation of the wedge framework is that the sources of emissions underpinning the BAU scenario were not completely described by Pacala and Socolow. Without such transparency it is difficult to delineate between mitigation efforts which are embedded within the BAU scenario (i.e.

virtual wedges) and those which are additional (i.e. stabilisation wedges). The framework could be improved as a benchmarking tool if the BAU scenario were completely described, removing this ambiguity around additionality.

While efforts were made to calculate the combined uncertainty of each of our estimates, if no uncertainty was presented for historical estimates, we could not objectively quantify a level of uncertainty. In addition to the more obvious uncertainties in our input data and assumptions, in some cases only aggregated global datasets and global average estimates of other parameters were available. These calculations could not consider regional factors or their effect on our estimated emissions savings. Such estimates could be refined using country level data which could then be aggregated to build a more accurate assessment of the emissions saved by a strategy. This would require higher resolution data which for some wedges would be impossible to obtain at present. More specific limitations relating to our assessment of individual mitigation strategies are discussed at length throughout section 1 of the SI.

4. Results

Figure 2 and table 3 show the annual and cumulative emissions reductions achieved by all wedge strategies under the *recalculated* scenario. Corresponding results for the *rounded* scenario are available in section 2 of the SI.

Despite rising affluence and the uptake of sports utility vehicles (SUVs), the vehicle efficiency and use strategies accrued the greatest cumulative emissions savings, on track for 2.30 wedges. Hydrogen and electric vehicles contributed negligible emissions savings as they represented less than 0.3% of the global fleet as of 2017. Ethanol similarly had little impact due to the emissions incurred during production (table S1). Personal transport mitigation strategies are on track to achieve approximately one-third of the seven-wedge target—driven almost solely by improved vehicle efficiency and reduced vehicle utilisation.

Although wind and solar power now form half of global investment in new generating capacity, they

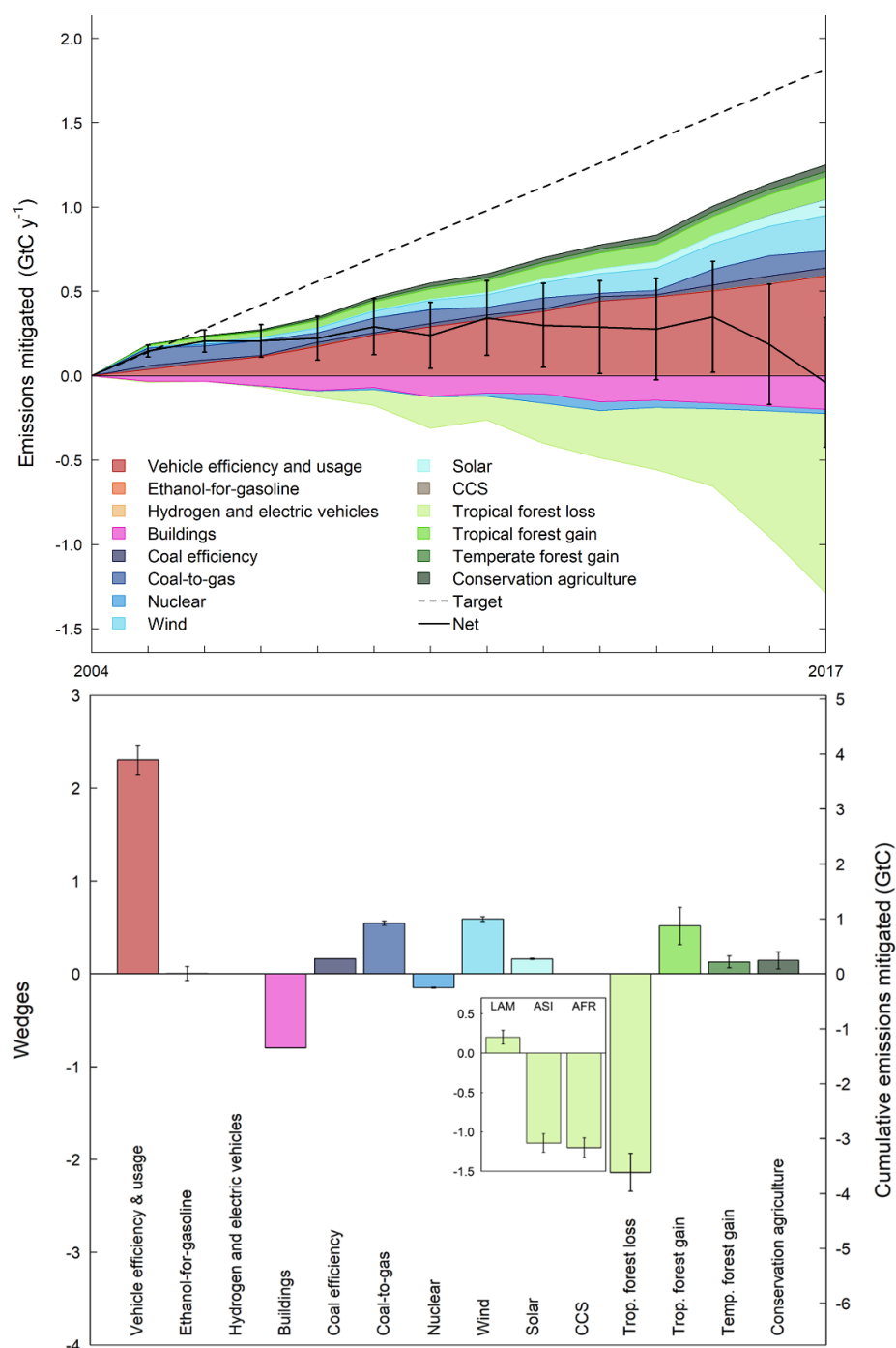


Figure 2. Emissions mitigated by wedge strategies under the recalculated scenario. (top) Time-series of emissions mitigated by wedge strategies compared to the mitigation efforts required to achieve the seven-wedge target and (bottom) cumulative emissions mitigated and number of wedges that each strategy is on track for under the recalculated scenario. The inset bar chart in the bottom panel shows the wedges achieved by reducing tropical forest loss disaggregated into three tropical regions: Latin America (LAM), Asia (ASI) and Africa (AFR). In the top panel, the emissions mitigated by tropical forest losses are presented as a two-year rolling average to smooth inter-annual variability in emissions savings. Unadjusted annual emissions savings are available in the supplementary data file.

are on track for just 0.59 and 0.16 wedges respectively. Improved coal-fired power plant efficiency and coal-to-gas fuel-switching are on track for 0.17 and 0.55 wedges respectively. Nuclear generation, which declined in the wake of Fukushima, is on track to contribute negatively. Overall, strategies in the power sector are on track to contribute less than one-fifth of the seven-wedge target.

With only four large-scale CCS facilities installed since 2004 across the three sectors proposed, their contribution towards reducing emissions was imperceptible. Emissions from buildings increased more rapidly than anticipated in the BAU scenario and therefore contributed negatively, offsetting approximately 60% of the emissions savings achieved in the power sector.

Table 3. Outturn and target change in primary variables and emissions savings under the recalculated scenario. Target values indicate the effort required to be on track for one wedge in 2054, except for strategies 14, 15a and 15b where targets indicate the effort required to achieve a half-wedge. SI unit conversion factors (3 sf): US mpg to km l⁻¹ = 0.425; miles to km = 1.61; barrels to tonnes of ethanol = 0.126.

Strategy (position in table 1)	Primary variable			Emissions mitigated (2004–17)	
	2004 ±95% CI	2017 Outturn ±95% CI	2017 Target (5th/95th percentile)	Outturn (GtC) ±95% CI	Wedges ±95% CI ^a
1–2 Vehicle efficiency and usage (NA) ^b	NA	NA	NA	3.90 ± 0.27	2.31 ± 0.16
Efficiency (US mpg)	23.7 ± 0.8	28.8 ± 1.2	28.1 (27.2, 29.1)	1.69 ± 0.11	1.00 ± 0.07
Usage (miles car ⁻¹ yr ⁻¹)	12 702	9910	10 691 (10 563, 10 807)	2.52 ± 0.18	1.49 ± 0.11
12 Ethanol for gasoline (million barrels d ⁻¹)	0.45 ± 0.06	1.54 ± 0.22	NA ^c	0.006 ± 0.126	0.003 ± 0.008
13 Hydrogen and electric vehicles (millions)	0.002	3.10	NA	0.0034 ± 0.0005	0.0020 ± 0.0003
HFCEVs (millions)	0	0.004	968 (724, 1459)	<0.0001	<0.0001
BEVs (millions)	0.002	1.92	403 (356, 464)	0.0024 ± 0.0004	0.0014 ± 0.0002
PHEVs (millions)	0	1.18	678 (594, 788)	0.0010 ± 0.0002	0.0005 ± 0.0001
3 Buildings (GtC yr ⁻¹)	1.88	2.34	1.88	−1.35	−0.80
4 Coal efficiency (lower heating value efficiency)	35%	38%	43%	0.28	0.17
5 Coal-to-gas fuel-switching (since 2004) (TWh)	0	786	2028 (1947, 2116)	0.92 ± 0.04	0.55 ± 0.02
9 Nuclear power (TWh yr ⁻¹)	2616	2488	3918 (3872, 3967)	−0.25 ± 0.01	−0.15 ± 0.01
10 Wind power (TWh yr ⁻¹)	84	1142	1386 (1340, 1435)	1.00 ± 0.04	0.59 ± 0.02
11 Solar power (TWh yr ⁻¹)	3	463	1302 (1259, 1354)	0.27 ± 0.01	0.16 ± 0.01
6–8 CCS (GtC captured yr ⁻¹)	0	0.001	0.26	0.002	0.001
14 Tropical tree cover loss (Mha yr ⁻¹)	8.3	15.7	6.1 (6.1, 6.2)	−3.61 ± 0.34	−2.14 ± 0.20
15a Tropical tree cover gain (Mha)	0	26.8	26.0 (19.6, 38.7)	0.87 ± 0.34	0.52 ± 0.20
15b Temperate tree cover gain (Mha)	0	16.9	65.1 (46.3, 110.3)	0.22 ± 0.11	0.13 ± 0.06
16 Conservation agriculture (Mha)	75.5	201.4	945 (636, 1975)	0.24 ± 0.16	0.14 ± 0.09

^a The number of wedges ‘on track for’ can be higher/lower than would be expected by comparing outturn change to the target because the outturn change could be higher/lower than the target in previous years.

^b The total emissions mitigated by this strategy is lower than the sum of contributing strategies as interactions between vehicle efficiency and usage diminish the impact of one another.

^c Ethanol is assumed to have higher well-to-wheel carbon emissions than gasoline in some years (table S1), therefore we could not calculate a target for adoption consistent with achieving a wedge.

Tree cover gains in the tropical and temperate zones stored modest amounts of carbon, on track for 0.65 wedges. Limited adoption meant that conservation agriculture practices contributed only small emissions savings. In contrast, tree cover losses in the tropics contributed substantial additional emissions relative to BAU. In Asia and Africa, accelerated rates of loss put these regions on track for −1.14 and −1.20 wedges respectively (figures S2–S4). In Latin America, reduced loss rates between 2004 and 2015 resulted in significant emissions savings, but

record losses in 2016 and 2017 reduced this progress to just 0.2 wedges overall (figures S2–S4). On net, land-based mitigation strategies are on track to negatively contribute −1.4 wedges.

Overall, net cumulative emissions savings show that we are on track to achieve just 1.5 ± 0.9 wedges, falling well short of the seven wedges targeted by Pacala and Socolow. Between 2004 and 2015 net mitigation efforts were on average around 40% of the level required to achieve seven wedges; however, in 2016 and 2017 this effort decreased sharply due to

increased rates of tropical tree cover loss. In 2017, outturn emissions exceeded BAU emissions and thus net emissions savings became negative. Therefore, while net cumulative emissions savings over the entire period suggest modest progress, if high rates of tropical tree cover loss persist then the emissions saved in other domains will be mostly, if not completely, offset and net progress will continue to stagnate.

At the 95% confidence interval, total cumulative emissions savings show we are on track for 0.6–2.3 wedges. Most uncertainty stems from estimated rates of biogenic carbon accumulation and emissions following tree cover losses, but uncertainties regarding the carbon intensity of conventional vehicle transport, life cycle emissions of ethanol, and carbon storage following conservation agriculture are also influential (see section 1 of the SI). The true uncertainty will be larger as some wedges have potentially significant but unquantifiable uncertainties, such as the true rate of tree cover losses and gains [33].

5. Discussion

This retrospective analysis paints a mixed picture of global energy and land use transformations. While some sectors of the economy have made substantial progress in reducing emissions, improvement has been much slower or even negative in many others.

Global average fuel economy has improved by nearly a quarter relative to 2004, driven primarily by the adoption of fuel economy regulations which now cover most major vehicle markets [30]. On average, improvements in fuel economy are 60% faster in countries with fuel economy regulations than countries without such regulations [30]. Historically, fuel economy had improved most rapidly in developed economies; however, this progress has slowed in recent years, most notably in Europe. From 2015 onwards, fuel economy improvements in Europe reversed as shares of more efficient diesel power trains declined following the ‘diesel-gate’ scandal in which vehicle manufacturers illegally adapted fuel economy test procedures to comply with emissions standards [34]. Another important driver of slowing fuel economy improvements in developed economies is the increased uptake of larger and less economical vehicles (e.g. SUVs) [30]. In contrast, fuel economy improvements have accelerated in developing economies, particularly in China and other Asian countries, as new and more stringent fuel economy regulations continue to drive progress [30]. Despite reported improvements, the ever-increasing gap between laboratory tested fuel economy and that reported under real-driving conditions, which is as high as 40% in Europe, has brought the effectiveness of fuel economy regulations in to question [35, 36]. Left unclosed, this gap will continue to cloud our

understanding of personal transport emissions and attenuate the ‘real world’ effects of fuel economy regulations.

Vehicle use intensity (distance travelled per car) fell by more than a quarter between 2004 and 2017. The regional drivers of declining vehicle use intensity are less clear than for other strategies due to limitations of the available data (see section 1.2.1 of the SI). The decline appears to have been driven by three key trends across major vehicle markets. Firstly, in Europe, and to a lesser extent the US, vehicle use intensity has declined gradually since 2004, primarily as a result of the lower reliance on cars in urban areas [37, 38]. Secondly, vehicle use intensity has fallen rapidly in China, driven primarily by a declining share of high-mileage taxis and a corresponding uptake in lower-mileage private vehicles [39]. Thirdly, a regional shift in the share of the global fleet of cars towards India and China (from 4% in 2004 to 20% in 2017), where vehicle use intensities are below the global average, has also contributed to a declining global average [39, 40].

High upfront costs relative to conventional cars and insufficient public charging infrastructure present barriers to the adoption of hydrogen and electric vehicles, meaning they are still at low (<1%) global penetrations [41, 42]. Rapid growth in electric vehicle markets in China, Europe and the US indicates that these barriers are not insurmountable; however, demand for combustion vehicles continues to grow. Life cycle carbon emissions and other sustainability concerns present substantial barriers for reducing emissions by substituting ethanol for gasoline [43–45].

Deployment of wind and solar power has been substantial, particularly in China, Europe and the US, and both technologies are following exponential growth trajectories which, if continued to 2054, will contribute significantly more than a wedge each [11]. Coal-to-gas fuel-switching in the power sector has achieved rapid emissions reductions in Europe and the US. If spare gas capacity already exists, fuel switching does not require several years to amount to material emissions savings, but is easily reversed while spare coal capacity remains [46]. As with combustion engines, increased deployment of gas-fired power generation cannot be a long-term solution to climate change. As over one-third of the world’s electricity is generated from coal [47], improving the efficiency of coal plants presents a substantial opportunity to reduce emissions. However, even at the state-of-the-art efficiency (~40%) coal plants emit 70% more carbon than an average gas plant today [48], hence the priority is rapid coal phase out. Nuclear generation declined substantially following the Fukushima-Daiichi disaster, not just in Japan but in nations across the world, with a growing number of nations committing to nuclear phase-out [49]. Nuclear power is also hindered by high construction cost

overruns in some countries, particularly outside Asia, weakening the economic case for new nuclear build [50].

In contrast to power and transport, progress in reducing emissions from buildings has been negative, though this trend is not reflected in all nations. In some developed nations (e.g. UK and Germany), stringent energy efficiency policies and fuel-switching to natural gas and electricity has meant that building emissions have been falling for over a decade [51]. In other developed nations (e.g. US and Japan), increased ownership of electrical appliances and uncoordinated energy efficiency policies have continued to drive emissions growth in buildings [51]. However, the most important trend in buildings is the increased access to adequate housing and energy services in developing countries, where living standards and energy demand are rising fastest [51]. Reversing recent emissions growth in buildings will require well-enforced, pro-active energy efficiency policies [52], and nowhere will this be more important than in developing countries.

To date, so few CCS facilities have been built that their impact on global carbon emissions has been imperceptible. CCS is not being deployed at scale because the incremental costs of capture and the development of transport and storage infrastructures are not adequately compensated by market or government incentives [53]. While the technological maturity of CO₂ capture options has improved considerably over the past decade, costs have barely fallen due to limited learning in commercial settings and increased resource and energy costs [54]. The perceived risk of long-term CO₂ storage is a further barrier to deployment [55].

Tree cover gains in tropical and temperate regions stored modest amounts of carbon to 2017; however, these emissions savings were completely overwhelmed by unrelenting tropical tree cover loss. In Asia and Africa, tree cover loss rates increased substantially between 2004 and 2017, while loss rates in Latin America declined up until 2016. In Asia, palm oil plantations are the primary driver of tree cover losses in the hotspots of Malaysia and Indonesia, although subsistence agriculture is an important driver of losses elsewhere [56–60]. In Africa, subsistence agriculture is preeminent, but industrial-scale clearing for commercial agriculture has become more widespread in recent years [57–60]. In Latin America, commercial cattle ranching and row-crop agriculture, particularly soy, are the main drivers of tree cover loss [56, 57, 59, 60]. Against these drivers, establishment of protected areas, enhanced law enforcement and a moratorium on soy from recently cleared forests led to declining rates of tree cover loss in Latin America between 2004 and 2015 [60]. However, in 2016 and 2017 record tree cover losses were reported, driven primarily by natural and human-induced fires (i.e. land clearance for agriculture) [59–62].

The rapid reversal of progress in Latin America highlights the fragility of tropical forests and the importance of long-term commitments to conserve tropical forests. To incentivise conservation, landowners require financial support that covers the transaction, monitoring and opportunity costs from lost revenues of alternative land uses [52, 59, 60]. The UNFCCC REDD+ programme's voluntary carbon market is the latest in a long string of financial mechanisms aiming to incentivise forest conservation. However, the carbon market never truly materialised and financial support from bilateral donors is insufficient to support the projects already under development [63]. In the absence of well-designed financial incentives, private-sector commitments and supply chain initiatives, like the moratorium on soy from newly cleared land, are increasingly important to conservation [60]. In recent years, the number of these commitments has increased greatly, but few have led to measurable improvements [59, 64].

Conservation agriculture is now practiced across all continents. In addition to carbon mitigation, these practices can offer several co-benefits: better farm economy, improved yields, protection against soil erosion, and water and nutrient retention [65]. However, adoption to date has been slow due to low knowledge and awareness of the practices and their benefits [65].

6. Conclusion

We convert historic progress for 16 climate mitigation strategies (tables 1 and 3) into the common unit of climate stabilisation 'wedges' [15], finding that cumulative emissions savings put the world on track to achieve 1.5 ± 0.9 wedges, relative to seven required to stabilise global carbon emissions by mid-century. Compared to a target of 14 wedges, required to achieve net-zero CO₂ emissions by mid-century and limit warming to 2 °C [21, 22], the emissions savings reported here account for just 4%–16%. While we report modest cumulative emissions savings over the entire period, in 2016 this progress reversed due to rising emissions from tropical tree cover loss. Halting the loss of tropical forest remains a clear priority for climate mitigation, without which we are unlikely to achieve climate stabilisation [60, 66]. However, greater action on forests does not decrease the imperative for strengthened mitigation in the energy system [67]. If we consider only the mitigation strategies relevant to the energy system, where transformation appears to be gaining momentum, cumulative emissions savings are still less than half those required to stabilise emissions and a quarter of those required to reach net-zero CO₂ emissions by mid-century.

Pacala and Socolow [15] showed that the portfolio of technologies required to 'solve the climate problem' has long been ready for deployment—the choice was simply between 'action and delay'. 15 years on,

we show that the world has opted to delay. Simplicity is the ultimate sophistication, and we hope that by expressing the current state of global decarbonisation in simple terms we allow a broad audience to understand what has been achieved so far, and how this must drastically improve in the decades ahead.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Conceptualisation, N J and I S; methodology, N J; software, N J; formal analysis, N J; investigation, N J; data curation, N J; writing—original draft, N J; writing—review and editing, N J and I S; visualisation, N J and I S; supervision, I S and R G; funding acquisition, N J and I S.

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