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Recalibrating climate prospects

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Abstract

IPCC's 2018 *Special Report* is a stark and bracing reminder of climate threats. Yet literature, reportage, and public discourse reflect imbalanced risk and opportunity. Climate science often understates changes' speed and nonlinearity, but Integrated Assessment Models (IAMs) and similar studies often understate realistic mitigation options. Since ~2010, global mitigation of fossil CO_2—including by often-uncounted modern renewable heat comparable to solar-plus-wind electricity—has accelerated to about the pace (if sustained) needed for a 2 °C trajectory. Mitigation has uncertainties, emergent properties, feasibility thresholds, and nonlinearities at least comparable to climate's, creating opportunities for aggressive action. Renewable electricity's swift uptake can now be echoed as proven integrative design can make end-use efficiency severalfold larger and cheaper, often with increasing returns (lower cost with rising quantity). Saved energy—the world's largest decarbonizer and energy 'source' (bigger than oil)—can then potentiate renewables and cut supply investments, as a few recent efficiency-centric IAMs confirm. Optimizing choices, combinations, timing, and sequencing of technologies, urban form, behavioral shifts, etc could save still more energy, money, and time. Some rigorous engineering-based national studies outside standard climate literature even imply potential 1.5 °C global trajectories cheaper than business-as-usual. A complementary opportunity—rapidly and durably abating hydrocarbon industries' deliberate upstream CH_4 releases from flares and engineered vents, by any large operator's profitably abating its own *and others'* emissions—could stabilize (or more) the global methane cycle and buy time to abate more CO_2. Together, these findings justify sober recalibration of the prospects for a fairer, healthier, cooler, and safer world. Supported by other disciplines, improved IAMs can illuminate this potential and support its refinement. Ambitious policies and aggressive marketplace and societal adoption of profitable new abatement opportunities need not wait for better models, but better models would help them to attract merited attention, scale faster, and turn numbing despair into collectively powerful applied hope.

'To be truly radical is to make hope possible, rather than despair convincing' (Williams 1989). Though 'hope is a stance, not an assessment' (Lappé 2018), a proper balance between hope and fear—a constructive balance, since people cannot be depressed into action—recedes when the public tone is set by statements like this from a prominent journalist's special feature filling an entire issue of *The New York Times Magazine* (Rich 2018):

> The odds of succeeding [in holding the rise in global average temperature below 2 °C], according to a recent study based on current emissions trends, are one in 20.…The climate scientist James Hansen has called two-degree warming 'a prescription for long-term disaster.' Long-term disaster is now the best-case scenario.

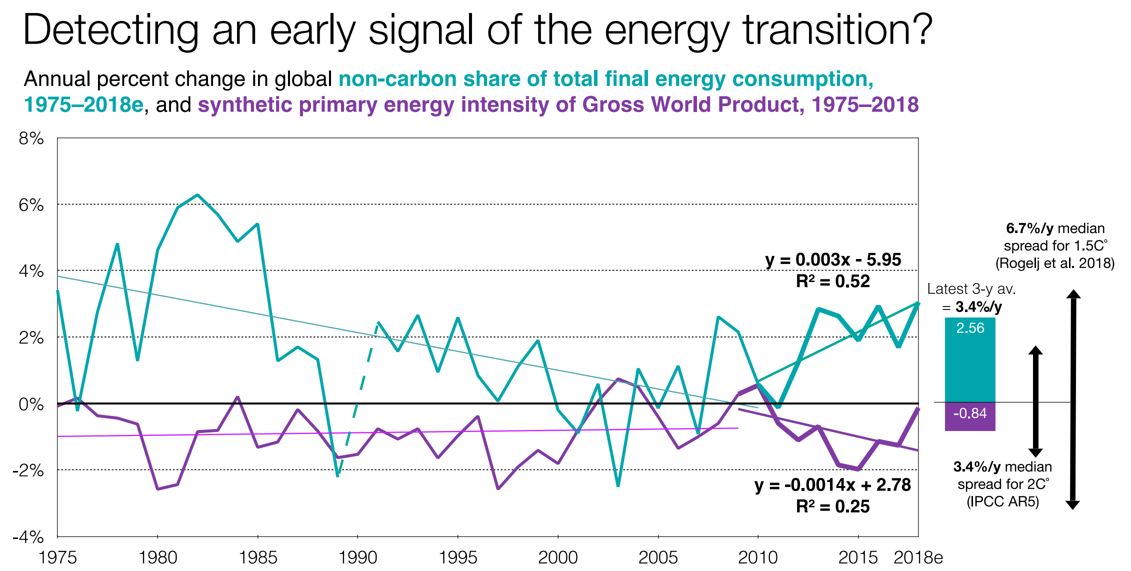

Figure 1. Suggestive pattern-breaking post-∼2010 behavior (heavy lines) in the rising non-fossil-fuel share of global total final energy consumption (TFEC, aqua) and in the falling primary energy used to produce a dollar of global GDP_{PPP}. The magenta energy intensity series is synthesized from BP primary energy consumption divided by World Bank global GDP_{PPP} to avoid technology-inconsistent primary-energy accounting conventions in the IEA dataset.,[18, 19] IEA primary energy intensity, graphed for comparison in supplemental material, part 1 (available online at stacks.iop.org/ERL/14/120201/mmedia), behaves similarly, but its 2009–18 regression shows a steeper trend and better fit ($y = -0.0024x + 4.77, R^2 = 0.38$) than the graphed synthetic intensity series, which is therefore conservative. Sources: IEA online database (TFEC); BP (2019, using the substitution method[18]) for renewables (except renewable heat data from the IEA online database, confirmed by IEA (2018c), p 258, figure 6.6, subtracting BP 'biofuels' from IEA 'other renewables'); World Bank online World Development Indicators (real GDP_{PPP}) accessed July 2019; IPCC AR5 (2 °C bar); Rogelj *et al* (2018a) (1.5 °C bar). Not smoothed or normalized for weather, business cycles, or other exogenous factors; 'well below 2°' conservatively approximated as 2°.

Yet that recent study's 5% odds (Raftery *et al* 2017) assume global GDP's carbon intensity will fall only at the same average rate (∼1.9% yr^{-1}) to 2030 as it did in 2012–18 (1.91% yr^{-1} average annual rate of change in total energy-related CO_2 emitted per unit of real global GDP_{PPP}). But the approximate decomposition graphed in figure 1 for 2012–18 to illuminate the underlying causes of that reduced carbon intensity totals nearly twice as big, 3.68% yr^{-1}, and its trends are accelerating. The causal factors underlying the *Times* article's 'current emissions trends' are actually from 1960 to 2010 and seem to have ended then.

When the Paris Agreement entered into force in late 2016, the annual rate of cutting the carbon intensity of the global economy, using the approximate metrics graphed below, was trending upward through 4.6% yr^{-1}. That's 2.7 times higher than the 1.7% yr^{-1} average decline for 1991–2010; 1.3 times the ∼3.4% yr^{-1} required[7] through 2050 for a 2 °C trajectory; and 0.7 times the ∼6.7% yr^{-1} required for 1.5 °C (Rogelj *et al* 2018a, SM table 3). It is also within striking distance of UN Sustainable Development Goal 7.3's doubling of the 2015 rate of global energy efficiency gain by 2030[8]. The definitive direct metric, fossil-energy carbon per real global GDP_{PPP} dollar, fell 2.64% yr^{-1} in the favorable years 2014–16—two-fifths faster than the *Times* story's source (Raftery *et al* 2017) assumed to 2030. Far safer but harder is the aspirational Paris goal of 1.5 °C average warming, consistent with mitigation pathways only sparsely modeled until recently (Rogelj *et al* 2015, Luderer *et al* 2016, Bertram *et al* 2018, Grübler *et al* 2018, Holz *et al* 2018, McCollum *et al* 2018). Yet the stronger mitigation tools this requires are now emerging.

Of course, the most critical metric is the greenhouse gas concentrations caused by emissions, notably 2018's alarming new record of 37 $GTCO_2$ yr^{-1} (Jackson *et al* 2019). Emissions depend on activity times intensity. Reducing energy and carbon intensities is our focus here to cut emissions regardless of GDP's exogenous and unknowable trajectory (further complicated by seldom-modeled feedbacks: lowering energy costs and climate harm could boost GDP or

[7] IPPC's AR5 2° scenarios span a 1.6–2.5%/y average 2010–2100 rate of decreasing primary energy intensity, combined with 1.1–1.5%/y decreases in carbon intensity. Those ranges' means add, for rough indicative purposes, to ∼3.4%/y, exceeding the >2.5%/y sum suggested by the Energy Transitions Commission for ⩽2 C° (ETC 2016). IEA (2018) agrees 1.7%/y is 'half of what is required to remain on track with the Paris Agreement'. The difference may trace back to IEA's 2011 450 scenario's 50% probability *vs.* the higher odds (e.g. 66%) widely required lately.

[8] R Kyte, personal communication, 20 Aug 2018, though Subratty (2017) seems to suggest, and IEA (2018b pp 13, 29) confirms, that the target rate is ∼2.7–2.8%, not twice IEA's reported rate of 2.8%/y for the agreed 2015 base year. Perhaps the discrepancy reflects IEA's and the World Bank's dispute about whether to use a multi-year moving average to even out fluctuations like those shown in figure 2.

raising them reduce it). GDP measures gross economic output, not net human welfare or happiness, so we prefer explicit physical activity metrics, but GDP remains conventional shorthand for a key emission driver (Raupach *et al* 2007). In 2000–10, lower energy/GDP cut average decadal CO_2 emissions by 5 GT yr^{-1} while population growth raised them by 3, higher carbon intensity by <1, and higher GDP/capita by 6, for a net total of 6.8 more $GTCO_2$ yr^{-1} than in the previous decade (IPCC 2014, p 9). Standard models assume average ~2.3% yr^{-1} GDP growth in 1990–2100 (Nakićenović *et al* 2000, p 93). Broadly, our implicit GDP assumptions align with moderate (SSP-2) trajectories, i.e. GDP growth ~3.1% yr^{-1} 2010–50, though with wide divergence 2050–2100 (IPCC 2018). The encouraging intensity trends we report could help offset climate risks of faster GDP growth or reinforce climate risk reductions from slower GDP growth. As most political leaders strive to maximize rates of GDP growth, the main pragmatic tools at hand are powerful new ways to reduce intensities more and faster than even recent efficiency-and-renewables-centric models—reinforced, toward the end of our paper, by a novel accelerant from methane abatement.

Belatedly, haltingly, yet with gathering focus and force, humanity is responding to an existential threat. IPCC's October 2018 *Special Report on Global Warming of 1.5 °C* (IPCC 2018), encouragingly invited in the adoption of the Paris Agreement, is both a sobering reminder of that formidable threat and an invigorating recognition of emergent potential solutions. This article seeks to help analysis, reporting, and reflection catch up with gratifying recent developments, rebalancing the climate conversation in a spirit of neither optimism nor pessimism but of applied hope (UCB 2011). Neither complacency nor despair is warranted. We need not panicked short-termism but resolute commitment, blending incisive impatience with relentless patience and high ambition.

As insight and worry deepen, more climate scientists (e.g. Brown and Caldeira 2017, Schellnhuber 2018, Steffen *et al* 2018) are sharing profound concerns long kept mainly private. Moving at the cautious pace of science and policymaking (Oreskes Oppenheimer and Jamieson 2019), with publication lags compounded by slow diffusion into public and policy discourse[9], climate models conservatively underestimated the speed and nonlinearity of emergent climate change (Spratt and Dunlop 2018). We posit *integrated assessments and similar energy/economic studies based on those climate models also typically underestimate, at least equally, many large, practical, and profitable options for mitigating climate change, especially on the demand side*. Offsetting these contrary biases, the outcome of what Jeremy Grantham calls 'the race of our lives' remains very much in play—if we double down on what works and embrace often-unexpected opportunities for action.

About 80% of 2017 world commercial final energy use (REN21 2019) and 81% of 2016 world commercial primary energy supply (IEA 2018a) came from fossil fuels. Their combustion emits CO_2 causing about two-thirds of radiative forcing (we will return to the rest later). Multiplying these two terms ($4/5 \times 2/3$), fossil fuels' CO_2 causes about half of radiative forcing. Mitigating that forcing requires 'drastic [energy] efficiency improvements'[10] (IPCC 2014, p 140) plus decarbonized energy supply. Efficiency is often informally assumed to be stagnant, largely completed, thoroughly understood, and a bit stodgy. Models' assumed efficiency potential varies but is generally modest. This article suggests the opposite. Even the International Energy Agency's Efficient World Scenario (IEA 2018b)—which could peak energy-related greenhouse gas emissions before 2020 and cut them 12% by 2040 despite doubled GDP, using only 7% more primary energy in 2040 than 2017, achieving over 40% of the Paris Agreement's 2 °C target with 3:1 financial returns from saved energy alone—may *under*state modern efficiency's profitable potential.

Energy efficiency presents new rapid-growth, declining-cost opportunities akin to renewables

Most analysts now realize that renewable sources of electricity and energy storage (Kittner *et al* 2017) are becoming bigger and cheaper at a phenomenal yet sustainable pace (Breyer *et al* 2016, Creutzig *et al* 2017, Haegel *et al* 2017) driven by increasing economic returns—the more we buy and learn, the cheaper the technology gets, so we buy and learn more, so it gets cheaper. Thus positive feedback occurs not only in climate but also in decarbonizing technology coevolving with policy (Abramczyk *et al* 2017). In 2017[11] 64% (REN21 2019), and in 2018 68% (FS-UNEP-BNEF 2019 p 26) of the world's net additions of electric generating capacity were modern renewables (i.e.

[9] Adding further inertia and hysteresis, evidence from a great many fields shows that researchers are typically 50% overconfident in their own results (Shlyakhter *et al* 1994). Integrated assessment modeling could make a significant methodological advance by recommending that practitioners recalibrate their models by comparing forecasts with actual outcomes and then adjusting their confidence intervals accordingly. Shlyakhter and Kammen (1992) develop a methodology for sea-level rise, and in Shlyakhter *et al* (1994) develop this metric for energy models.

[10] In the three end-use sectors (mobility, buildings, industry) that directly burn slightly over half the world's fossil fuel (IPCC 2014) and in the power plants, refineries, and other conversion systems that produce final energy for delivery to those sectors (Edelenbosch 2018).

[11] FS-UNEP-BNEF (2018), adjusted from that source's 61% by correcting the report's FS-acknowledged error of assuming BNEF's Feb 2017 forecast of 11 GW of net nuclear additions in 2017; the actual was 0.3 GW (IAEA PRIS), or 0.9 GW including US upratings (USNRC). Whether the 2018 value contains a similar conservatism is unknown.

excluding hydroelectric dams of $\geqslant$50 MW_e). Those increasingly cost-competitive or cost-*superior* technologies quietly passed nuclear power's electricity output in 2016 and an astounding one trillion watts' installed global capacity in mid-2017. That 1 TW capacity took about 15 years to build; the next TW will take about 4–5 years (Amin 2018). One TW of wind and solar power was installed by mid-2018—65-fold growth since 2000, over 4-fold since 2010—with the next TW expected by mid-2023 at 46% lower cost (BNEF 2018a). Thus both positive feedbacks and uncertainties in climate science may be mirrored by those in mitigation opportunities and their projected costs (Weyant 2017, Farmer *et al* 2019, Lovins 2019). Yet it is hard to find Integrated Assessment Models (IAMs) that foretold this renewable energy story—perhaps largely because conventional economic models' structures cannot easily (if at all) backcast or forecast increasing returns.

The International Energy Agency raised its annual *World Energy Outlook* series' long-term windpower forecasts by sixfold and its solar photovoltaic (PV) power forecasts by 23-fold during 2002–18. Yet reality moved faster: today's PV capacity exceeds 50 times IEA's 2002 forecast, lately adding each year more net new capacity globally than all fossil-fueled and nuclear additions combined, and adding 100 GW more than in the previous year. This growth drove down renewable prices, speeding growth: world levelized nominal prices fell *in 2016 alone* by 17% for utility-scale PV, 18% for onshore wind, and 28% for offshore wind (FS-UNEP-BNEF 2017 p 17), while the lowest bids fell 37% for Mexican PV and 43% for EU offshore wind (Kåberger 2017). Thus IEA's *World Energy Outlook* (2018c) predicted renewables would get 69%–77% of global electricity-generating investment in 2018–40, consistent with Bloomberg New Energy Finance's *New Energy Outlook*'s 76% (BNEF 2019). BNEF's *short*-term 1Q18 PV growth forecast rose >50% in a year, and its 18 June 2019 long-term PV forecast predicted global installed capacity of 2.4 TW by 2030 and 7.5 TW by 2050—surpassing the world's present *total* generating capacity of 7 TW.

In the first half of 2019 (Kåberger and Zissler 2019), China, India, the US, and Germany generated 36 TWh less from fossil fuels than in 1H18—the US and Germany cut fossil generation three times as much as China and India raised theirs—while the four nations' carbon-free generation rose by 139 TWh. Germany's windpower outgenerated lignite (and in June, solar beat both) as renewables neared half total net generation, up from 10% in 2000. India and China raised renewable output by more in two years than their nuclear output in 2018. Might renewables, reduced intensity plus slowing economic growth yet shrink global CO_2 emissions in 2019?

That's supply—and now the other shoe in the energy revolution is dropping. A new synthesis (Lovins 2018) argues that like renewables, and just as invisibly to today's canonical modeling methods, *the energy efficiency resource is severalfold larger and cheaper than had been generally accepted* (Graus *et al* 2009), and often exhibits increasing returns. That's less due to mass production of fast-learning, short-lead-time technology under innovative business and financial models than to *design* innovations in choosing technologies together to work optimally with each other, not separately so they work against each other (*id*).

With such integrative design methods swiftly evolving, efficient energy end-use is not a thoroughly characterized, slow-changing, dwindling-quantity, rising-cost resource, but an emergent, rapidly evolving, expanding-quantity, falling-cost resource. Its cost falls because optimizing buildings, vehicles and mobility systems, factories, equipment, etc as whole systems for multiple benefits, not as isolated parts for single benefits, uses not more and fancier devices but fewer and simpler devices—more artfully chosen, combined, sequenced, and timed (*id*, Elberling *et al* 1998). This opportunity is hard to capture with traditional economic theory or conventional modeling, which apply structurally different logic, but emerges clearly from careful, cutting-edge engineering practice. There is little evidence that these recent major advances in design practice and its empirical results are adequately accounted for in normative IAMs or other models.

These systemic opportunities and nonlinearities are hard to capture even in engineering-economic basic frameworks using conventional approaches. For instance, the widely used 'McKinsey curves' (supply curves of carbon abatement, e.g. Creyts *et al* 2007, Nauclér and Enkvist 2009, McKinsey&Company 2010) consider single measures as independent interventions whose sequential implementation raises marginal costs. However, by implementing measures in a bundle, whole-system optimization reduces overall costs[12]. The

[12] This is true of energy systems (e.g. Lovins and RMI 2011, Goldemberg 2011) and of energy supplies: when solar, wind and energy storage are all modeled not as a single-variate function of deployment, but as a function of both *total deployment* and *effort*, their rates of cost improvement are all strikingly similar (Kittner *et al* 2017). Similarly, improvements in solar cells help spur investment and improvement in energy storage, and vice versa. Similar but less-recognized synergies apply to energy efficiency. For example, many building models establish optimal levels of insulation or window U-values as individual interventions. Such methods will reveal that triple-pane windows or heat-recovery ventilation make no economic sense. However, when a whole passive house is costed, including triple-pane or better windows (the senior author's passive home uses superwindows that insulate like 16–22 panes) and heat-recovery ventilation, these exceed the costs of conventional designs by small margins, if at all, for several reasons. First, once a leaky building is air-tightened, the marginal benefits of going from better-than-double-pane windows, or to heat-recovery ventilation, are more attractive. Furthermore, such engineering approaches bring down heat demand so much that heating systems can shrink substantially, offsetting these efficiency measures' extra cost (NAS 2009 p 40: 'The net incremental first cost of achieving a 50 percent reduction in energy use through an integrated approach can be at or near zero; the savings from downsizing and simplifying HVAC systems generally pay fully for the additional costs of measures such as additional insulation, better windows, and daylighting….'). Very high- performance commercial buildings can even decrease capital costs per m^2, due to the value of rentable space, plenum height, floor-to-floor height, and structure saved by shrinking HVAC rooms, pipes, and ducts and by mass decompounding.

vast majority of climate and energy models, both bottom-up and top-down, are unable or at least challenged to capture systemic optimization even at an engineering level, let alone in the wider interplay of (radical) technology with societal changes (Geels *et al* 2017).

The IAMs that do emphasize energy efficiency—not the dominant practice, as elaborated below—nearly always assume point-value cost and performance for a limited set of specific technologies. These are sometimes augmented by innovations in usage, such as urban design that needs less driving (Güneralp *et al* 2017) or social-science methods that encourage mindful use (Creutzig *et al* 2016, 2018, Mundaca *et al* 2019)[13]. But such analyses aren't only at risk of being outrun by stunning innovation—e.g. LEDs, which in each decade got 30 times more efficient, 20 times brighter, and 10 times cheaper (Narukawa 2010), so they're set to save an eighth of the world's electricity (versus ~2005, estimated from De Alameida *et al* 2014). They also miss major categories so simple they're rarely acknowledged (see box).

> *An example of overlooked efficiency opportunities.* Using fat, short, straight pipes and ducts—not skinny, long, crooked ones—can cut their fluid-handling friction by ~80–90 +% (Stasinopoulos *et al* 2009, Lovins 2018). Since at least half the world's electricity powers motors, half to run pumps and fans (with pumping energy combatting mainly friction not gravity), this single opportunity—typically paying back in less than a year for retrofits, instantly for newbuilds—could in principle, if fully exploited worldwide, save about one-fifth of the world's electricity (*id*), equivalent to about half of all coal-fired electricity. Yet it's not in any national study, industry forecast, IAM, or (except Stasinopoulos *et al* 2009) engineering text, because it's not a technology; it is a *design* method. Few people think of design as a scaling vector. Most models can accommodate improvements only by single technologies or price signals, and IAMs are not granular enough to detect this ~4 $GTCO_2$ yr^{-1} missing term.

The compelling new evidence of far larger and cheaper efficiency opportunities spans all sectors (Wilson *et al* 2012, Lovins 2018)—not only the buildings sector (Ürge-Vorsatz *et al* 2012, 2013, 2015) as IPCC analyzes (Lucon Ürge-Vorsatz *et al* 2014). That is great news for climate, because reduced energy intensity—now the world's largest energy 'source,' bigger than oil[14]—invisibly delivered three-fourths of the 2010–16 marginal decarbonization of global GDP (IEA 2017 p 19), and more than renewables plus nuclear power even in 2017–18 when energy savings were the slowest in this decade (IEA 2019 p. 8). The same is true in the United States, where intensity reduction since 1975 has enabled 30 times more new energy services than doubled renewable output has done. Yet the ratio of headlines and attention is roughly the opposite, because renewables can be conspicuous while energy is invisible and unused energy is nearly unimaginable. As discussed below, nearly all of the all-sector IAMs (with a prominent exception noted below, Grübler *et al* 2018) now lag reality at least as much for potential energy efficiency gains as for renewable energy supplies, and often more so. Underestimating both these critical climate mitigations shrinks the solution space, cramps policy responses, and may result in buying costlier and risker options than we actually need, slowing mitigation and locking in more climate risk.

To be sure, global scale-up of energy efficiency, traditional or radical, faces many major and richly documented obstacles (NAS 2009, Boutons *et al* 2010). The integrative design methods needed to realize its increasing returns require not just physical but mental retrofits —'re-minding' designers, rewriting textbooks, revising curricula, and changing deeply embedded assumptions, habits, and metaphors. (E.g. the common metaphor of 'low-hanging fruit,' implying that larger savings will cost more, is really about eye-level fruit: the best practitioners look lower and see fallen-down fruit mushing up around their ankles and spilling in over the tops of their waders, and also higher, revealing fruit profusely growing back faster than they can harvest it. They typically also use a wide variety of tools to harvest all the fruit at once from a given tree, more cheaply than returning repeatedly to harvest it piecemeal.)

Fortunately, with many trillions of dollars' worth of net-present-valued (NPV) savings on the table, institutional and psychological barriers are starting to morph into business and policy opportunities. Recognizing far bigger but cheaper savings is the first step in capturing them. Energy and climate modeling must lead by fundamentally modernizing its methods and assumptions. Otherwise, its findings will increasingly diverge from the real opportunity space and will divert policy and investor attention away from these demand-side opportunities to socially and environmentally more controversial ones—less likely to succeed competitively and logistically—by continuing to emphasize supply-side and (unproven) CO_2-removal options, especially in overshoot and energy-intensive scenarios (e.g. Clarke *et al* 2014, Fuss *et al* 2014, Kriegler *et al* 2017). IAMs uniquely link 'mitigation strategies and technology portfolios to cumulative emissions budgets and, consequently, warming outcomes,' so they 'have become "gatekeepers of research" in the domain' (Mundaca *et al* 2019, p 344). Therefore, they must correctly describe the most important mitigations.

[13] The literature on behavioral economics and environmental psychology as applied to sustainable energy use is also revealing multiple interventions that highlight the importance of design (e.g. on the provision of information, choice settings) that complement technical measures (e.g. Abrahamse *et al* 2005, Allcott and Mullainathan 2010, Andor and Fels 2018, Pichert and Katsikopoulos 2008).

[14] E.g. 1990–2016 reductions in global energy intensity saved more energy in 2016 than oil supplied in 2016.

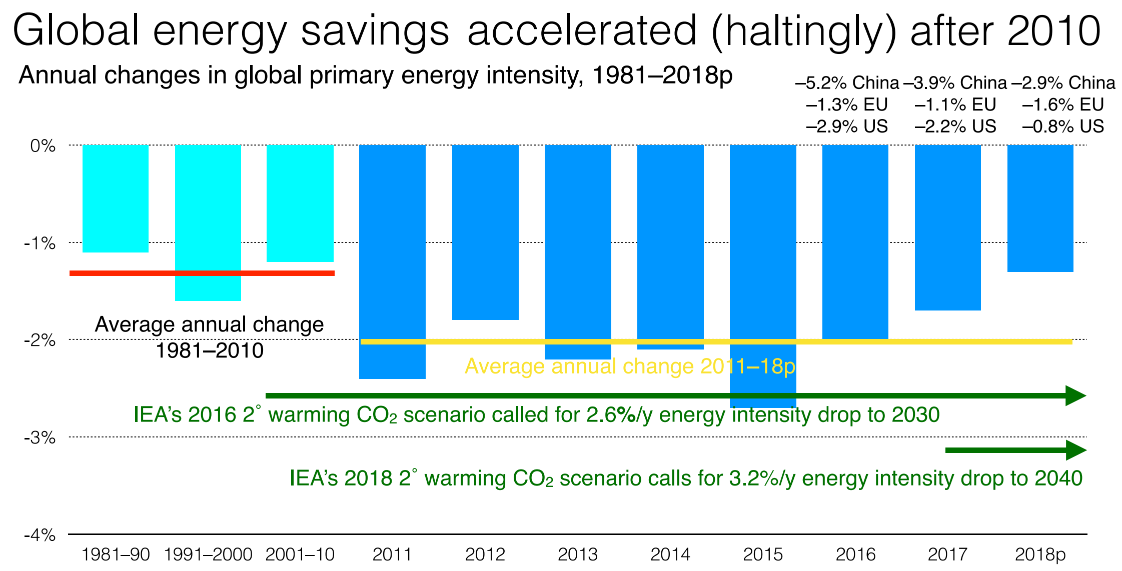

Figure 2. The International Energy Agency (IEA 2017, 2018, 2018b, 2019, all averaging annual rates of change without compounding) reports that global energy intensity (primary energy consumption per dollar of real GDP_{PPP}) fell nearly a percentage point per year faster during 2011–18 than in the previous three decades. The black text inserts above the three bars on the right show high sensitivity to Chinese and US fluctuations, detailed for 2011–17 in IEA (2018b), p 20, and for 2017–18 in the November 2019 edition (which, as this paper was in press, immaterially dropped the 2018 intensity reduction from the 1.3% shown to 1.2%, as China changed to −2.8%, EU to −2%, and US to +0.8%—3× the 0.26% rise shown for 2018 by USEIA and Federal Reserve October 2019 data). Prices no doubt influenced intensities, but econometric analysis seems unneeded here, and may add little insight: real global prices for diesel and gasoline fluctuated modestly in 2005–18 but ended the period virtually unchanged (IEA 2019b), while in the US, wholesale natural-gas real prices were volatile but fell ~3×, and US retail real electricity prices ended flat, now approximating mid-1970s levels.

Pre-2010 trends no longer constrain the present or future

Stern (2007) and Barker *et al* (2006), reviewing classical IAMs, found they did not actually analyze technological energy efficiency; nearly all used economic surrogates, a method Edelenbosch (2017) called 'stylized.' They assumed historic average rates of improving global aggregate energy intensity (or within about 0.5 percentage point of them—Rosen and Guenther 2015)—typically ~1.2% yr^{-1} in final energy during 1971–2010 (IPCC 2014, Fricko *et al* 2017). Those four decades, often called 'recent,' span transformation from an era when many experts seemed to reject any possibility of significant savings in supposedly-already-optimized market economies—modern energy efficiency began emerging only in the 1980s—to this decade's >2% yr^{-1} progress. Yet a 1.5%–2% yr^{-1} goal, which some might think ambitious, falls short of 7 out of 8 years' experience during 2011–18 (IEA data, figure 2), just as the supply-side goalposts are in rapid motion too. Where are they headed?

The many models that still extrapolate energy-intensity trends from the decades up to 2010 are missing this decade's seemingly pattern-breaking shift (figure 1), with early signals starting to emerge suggestively from noise. With the best fit starting in 2009[15], global energy intensity broke out of a holding pattern into decline, just as modern renewables began growing even faster. Figure 1's 2011–18 average rate of primary intensity decline, ~2.02% yr^{-1}, is two-thirds of IEA's (2018) ~3.2% yr^{-1} Paris Agreement target for 2 °C. In 2014–16, intensity reduction *plus* decarbonizing supply entirely offset global GDP growth's increase in CO_2 emissions, before the intensity drop retreated modestly in 2017 (IEA 2018, 2018b) after low oil prices, and further in 2018 (IEA 2019a, see supplemental data 1). If the world after 2010 sustained its 2011–18 rather than its 1971–2010 rate of primary energy intensity reduction, i.e. the yellow not the red line in figure 2, 2050 primary energy use would be two-fifths lower and 2100 use two-thirds lower—immense if not decisive progress[16]. And within such global averages,

[15] The global financial crisis was found to be an important driver triggering—at least initially—lower energy intensity. From a regional point of view, however, different trends were revealed compared to historical trends (Mundaca *et al* 2013, Mundaca & Markandya 2016).

[16] From 2010 to 2050 (2100), the difference between an average 1% and a 2% or 4% annual drop in energy intensity is respectively a 33% (59%) or 69% (97%) drop in long-term energy use. The 2.5%/y 2010–50 rate of the SSP1 storyline (van Vuuren *et al* 2017) matches the 2.5%/y maximum in IPPC's AR5 2C°-scenario database; the EMF27 results of nine IAMs suggest a 2 C° policy could achieve global averages of 1.3–2.9%/y with a 2.3%/y median (Sugiyama *et al* 2014). AR5's fastest average projected 2010–50 primary energy intensity reductions (IPCC 2014, p 426) are ~2.5%/y for OECD and ~3.7%/y for non-OECD, though EMF models often constrain projected purchases of profitable new technologies to fit 'people's actual behavior' (Rosen and Guenther 2015) under conditions that no longer exist and that entrepreneurs and activists aim to change as much as possible, so assuming those conditions is akin to driving while looking in the rear-view mirror.

examples abound of much faster savings already achieved in many places[17] by widely adaptable and adoptable means.

Strikingly, figure 1 shows that averaged over the past three years (2015–18e), the *combined* effect of primary energy intensity reduction plus increased share of decarbonized final supply[18] totaled 3.4% yr^{-1}—the same rate, if sustained, that IPCC AR5 found necessary for a 2 °C trajectory, and trending toward (though still well short of) the sustained ~6.7% yr^{-1} needed to 2050 for 1.5 °C (Rogelj *et al* 2018a, SSP1). Though trend is not destiny, the future is largely choice not fate, so despair is indeed as unwarranted as complacency.

To test figure 1, we must probe the data for underlying causalities. Recent shifts in annual rates of change reflect fluctuating denominators (energy use and GDP_{PPP})—especially labile during this decade's economic fluctuations and volatile weather. A skeptic might argue that diverse trendlines and even ambiguous slopes might be claimed for almost any short portion of such 'noisy' graphs. However, enough signal has lately emerged to show that the new trends graphed as heavy lines at the right side of figure 1 appear to reflect fundamentally new causes, not random fluctuations. Here's why.

Figure 2 shows how primary[19] energy intensity has fallen nearly one percentage point per year faster since around 2010 (best fit from 2009) than during the previous three decades.

This decade's faster intensity reduction reflects better technologies and designs, improved operations, and structural shifts, plus progress in mitigating numerous market failures and behavioral anomalies in buying energy efficiency, hence advances in exploiting business opportunities to correct them. Smarter public policies (Lovins and RMI 2011, Harvey 2019) are all synergistically raising the bar—ambitious building codes towards nearly zero-energy buildings, stringent minimum performance standards (including updating like Japan's market-led Top Runner programs), education and training, market-making, barrier-busting, desubsidization of fossil fuels, internalization of climate and other public costs, alignment of split incentives, PACE bonds, performance-based design fees, decoupling and shared savings for utilities, feebates for autobuyers,…, plus financing, market delivery, technology, and customer attention. Yet integrative design, not yet widely practiced or noticed, creates a huge new overhang of unbought and unsuspected efficiency that entrepreneurs and organizations like Rocky Mountain Institute (RMI) aim to shift from rare to routine.

On the supply side, figures 3(a), (b) validate figure 1's trend break (best fit from 2010), while also showing the need for more beneficial electrification of uses now fossil-fueled. Figure 3b's colorful forest of post-2010 renewable growth is new and large. The big surprise is the orange wedge at the top of figure 3(a), modern renewable heat: though seldom noted or analyzed, it supplied 4.2 percent of TFEC in 2017—3% more than solar electricity plus wind electricity, though they pulled 10% ahead in 2018. This large non-electric term does not appear to be included in the widely used BP database, whose 'geothermal, biomass, and wastes' and 'solar' terms match other databases' electricity-only outputs.

Since electricity was only 20% of 2015 global final energy, even very rapid growth in renewable electricity is strongly diluted by transport (32%) and heat (48%). Some important end-uses, such as low-temperature heat and light/medium mobility, should be largely saved, then efficiently electrified. But for some end-uses, renewably-derived heat or fuels may prove better and cheaper, so the fashionable goal of 'electrify everything' is a somewhat exaggerated oversimplification. It's therefore encouraging that ~16 EJ yr^{-1} of previously little-noticed modern renewable heat is already being delivered.

Nearly all IAMs' understatement of energy efficiency is due not only to outdated trend data and limited technical granularity of the demand side but also to imbalanced analytic methods and structures and to some questionable assumptions, such as all potential

[17] Actual average annual energy-intensity reductions include China's 7.0% 1991–5 and 4.8% 2012–16, Japan's 3.4% 1975–81 and 3.5% 2011–16, Tokyo's 5.4% 2002–12, Denmark's 6.9% 1997–2000 and 4.6% 2011–16, Ireland's 4.8%/y 2007–16, and California's 3.2% 1998–2005 and 2.8% 2010–15. Some exceptional medium-sized and large companies, too, have sustained 6–16% over periods of years.

[18] This is a conservative, intuitively straightforward, easily explained approximation for decarbonizing the global economy. J G Koomey (personal communication, 26 Oct 2018) correctly notes that our choice of metrics in Figure 1 may somewhat understate the total reduction in fossil CO_2 emissions per dollar of global GDP, because it counts substitution of carbon-free sources for fossil-fueled ones, and resulting avoidance of thermal-power-plant conversion losses, but omits substitution of less- for more-carbon-intensive fuels. That effect could also be captured by combining final energy intensity of global GDP with two terms in Koomey *et al* (2018)'s extended Kaya decomposition, i.e. reduction in Total Fossil Carbon per unit of Total Primary Energy (Direct-Equivalence Method). The results are then roughly comparable to Figure 1, although until 2013–16, when its R^2 exceeds 0.6 ($n = 4$), its fit is not as good as figure 1 shows.

[19] IEA's primary energy counts nuclear but not solar and wind electricity at triple value—the amount of fossil fuel that a traditional thermal power plant would have burned to produce it (the Substitution method: Koomey *et al* 2018). BP primary energy data in mtoe (not TWh) use a triple-value convention for *all* primary electricity. Figures 3(a), (b) avoid this issue—and confusion between primary energy saved by efficient use or structural change with savings from switching to non-combustion sources—by using IEA final energy (hence the Direct Equivalence method, *id*).

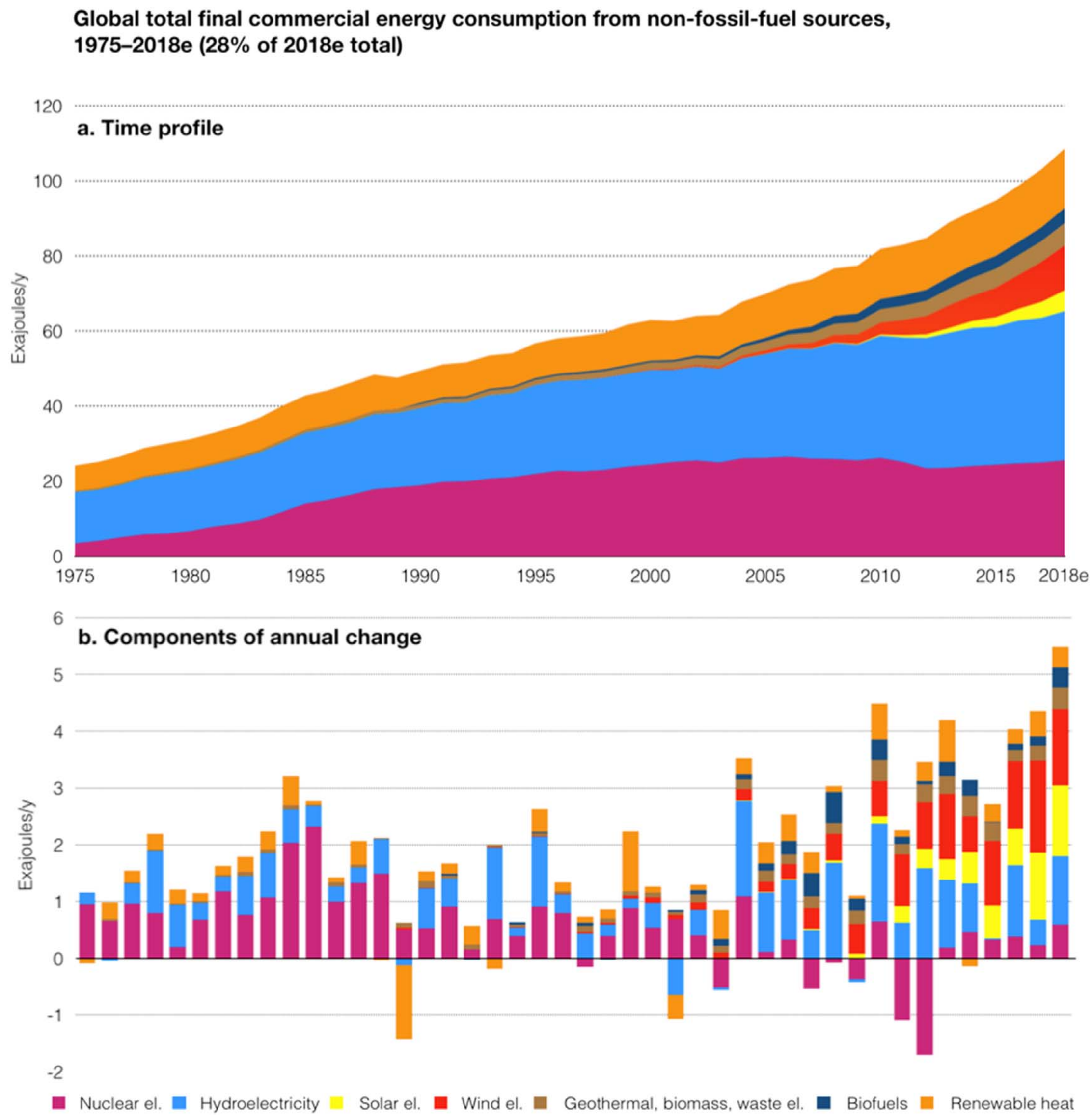

Figure 3. The 1975–2018 growth of global Total Final Energy Consumption (TFEC) from non-fossil-fuel sources of electricity, heat, and fuels (panel a) accelerated sharply from ~2010 as new technologies supplemented stagnant old ones, sprouting a new forest at the right side of panel b. All data are final except 2018 modern renewable heat, estimated from 2017 using its average 2014–17 3 years' growth rate, and 2018 TFEC, which is preliminary. Energy consumption here and throughout this article excludes nonfuel uses. Primary electricity is converted at 3.6 MJ kWh^{-1} using the Direct Equivalence method, rather than at 4.4 TWh/Mtoe using the Substitution method.[18] Sources: BP (2019) for all resources, except renewable heat (which excludes traditional biomass—7% of 2017 TFEC) from IEA online database, verified within ~1% from IEA (2018c), p 258, figure 6.6, by subtracting BP 'biofuels' from IEA 'other renewables', and confirmed directly with IEA Statistics. (BP does not appear to show renewable heat, while IEA aggregates biofuels with biomass. BP's biofuels data begin in 1990.) REN21 (2019) draws very similar renewable heat data from IEA and reports it totals 4.2% of 2017 TFEC, comprising approximately 89% biomass, 9% solar, and 2% geothermal. Year-to-year fluctuations reflect irregular hydropower additions and hydrology; wind and solar output growth are steadier. Nuclear additions—stressed by uncompetitive operating costs, lack of a newbuild business case, and operational problems—struggle to outpace retirements (Schneider *et al* 2018, 2019). Nuclear decline probably benefits climate due to such costly-to-build-or-run resources' opportunity cost (Lovins and Palazzi 2019, Lovins 2019c).

cost-effective efficiency's being achieved in baselines. Supplemental material, part 2, critiques these deficiencies—and offers encouraging news about recent improvements, which we amplify next. State-of-the-art IAM scenarios confirm that falling energy intensity is not only vital for meeting stringent mitigation goals (Clarke *et al* 2014, Riahi *et al* 2015, Rogelj *et al* 2015, Kriegler *et al* 2018); it is *the* most important variable, more important than economic growth, and is the main cause of SSP1–SSP5 scenarios' widely divergent long-term energy demands. Improving the previously sparse modeling of energy efficiency's potential is therefore revealing remarkable new mitigation opportunities.

Initial IAM efficiency modeling is proving its gamechanging value

Recently some IAMs using highly diverse and simplified methods[20] have begun explicitly representing specific end-uses, chiefly light-duty vehicles (Edelenbosch *et al* 2017a), steel and cement production (Edelenbosch *et al* 2017), space-heating, and home appliances, and taking aggregated account of their canonical efficiency potentials. Some results are dramatic, such as 3–4-fold faster non-OECD industrial intensity reduction with global industrial intensity declining as much as 2.1%–3% yr^{-1} (Edelenbosch *et al* 2017), and in one case, complete decarbonization of passenger transport—all 'clear break[s] with historical trends' (Edelenbosch *et al* 2017a). The SSP1 model puts forward important aspects of energy savings, yet as argued above, more granular and specific energy efficiency measures can reveal more powerful technology portfolios ripe for better design (van Vuuren *et al* 2017). Using such complementary modeling tools as decomposition analysis, national-level assessments under stringent emissions targets reveal important energy and carbon savings that are not fully captured in global IAMs (Wachsmuth and Duscha 2018).

More broadly, explicitly modeling just some end-use efficiency options generally finds severalfold bigger (Edelenbosch 2018, p 131) and considerably cheaper energy savings and carbon abatements, increasing modelers' motivation to enrich end-use detail and to make what they call 'energy system models' focus at least as much on demand as on supply[21]. But can grafting small engineering-based submodels of the easiest-to-model subset of end-uses onto complex macroeconomic simulations reveal much of efficiency's promise? And is the obstacle to proper energy efficiency modeling (Creutzig *et al* 2018) really inherent complexity, or is it remediable unfamiliarity and inattention? Is it unavoidably much harder to model energy efficiency as dynamic, complex, nonlinear, and multilayered (cutting across behavioral, economic, environmental, organizational, institutional, and technological layers, among others) than to do the same on the supply side, where data are richer and easily available, and where IAMs traditionally and understandably focused most of their effort? Encouraging evidence is starting to unfold.

After two global IAM studies found that faster and stronger demand-side measures could achieve 1.5 °C trajectories (Rogelj *et al* 2015, Luderer *et al* 2016; IPCC 2018 lists other literature at p 2–23), important new evidence of a demand-side bonanza emerged from Grübler *et al* (2018). Their impressive Low Energy Demand scenario within the Detailed Process IAM framework combines a bottom-up activity and demand assessment for four end-use services, with emphasis on urban form, noneconomic behavior-science insights, and other non-technological opportunities—creatively expressed through a set of stylized assumptions synthesized without the IAM framework before utilization within it. This combination achieves 2050 final energy demand 44% below SSP1, the most sustainable SSP pathway narrative scenario. *Supply-side investments fall by approximately 2–3-fold*—saving from one to several trillion dollars *per year* by 2050 (without netting out the cost of the savings, no doubt lower but not yet evaluated)—and even if long-run demand rises 50% above the predicted level, this scenario remains consistent with a 1.5 °C goal. It strongly advances the Sustainable Development Goals, and needs no carbon removal beyond natural systems.

Yet this scenario's astonishingly low demand (245 EJ_{final} in 2050)—the lowest yet in any IAM 1.5 °C scenario, and featured in IPCC's 1.5 °C Special Report (2018)—is technically conservative. It could be substantially lower if it included more-aggressive but proven and cost-effective technologies than, say, 3 $L/100$ km autos in 2050—e.g. the carbon-fiber-body, battery-electric, 1.7 $L_{equiv}/100$ km (German test cycle) 4-seat car profitably produced in midvolume since 2013, or a 0.9 $L_{equiv}/100$ km 2013 2-seater from another major automaker. Nor does the 2050 opportunity allow any significant intensity drop in airplanes (3–5× improvement looks attractive and feasible (Lovins and RMI 2011) with a customer-led leapfrog—Lovins 2019a), more than 3× in heavy trucks (Lovins and RMI 2011), etc (as in most IAM

[20] Some IAMs drive technology change by learning curves, most by price (typically influenced by policy); IPCC notes (IPCC 2014 at 426) that efficiency to a 'significant extent' is 'driven by other factors such as technological progress and changing preferences with rising incomes, and Sugiyama *et al* (2014) at figure S15 find huge scatter in implicit carbon-price elasticities of energy intensity. Most integrated models are able to project structural and technological change only at an aggregate level, although some include explicit assumptions for certain sectors…'. Many models' workings are opaquely described. Their structures and emphases vary widely; even data for the same base years may not match. Partial equilibrium models can incorporate some technology-specific choices while weakening its macroeconomic context, while most computable general equilibrium models derive energy intensity only from technology-blind substitutions between capital, material, labor, and energy inputs. Some modern models, increasingly, are hybrids of convergent bottom-up and top-down approaches (Sugiyama *et al* 2014). Broadly, most models today are much better than those reviewed by Barker *et al* (2006), whose net-cost differences he tried to analyze by regressions based almost entirely on model structure without directly comparing assumed gross technology costs (Rosen and Guenther 2015). However, in e.g. the influential SSP narrative scenarios (Fricko *et al* 2017), technology cost evolves only on the supply side, and efficient use is 'not explicitly modeled,' so although it's a 'key enabling driver,' projected improvements 'remain vastly different' (>3-fold by 2100). More general concerns with IAMs are summarized by Ackerman *et al* (2009), DeCanio (2003), Scher and Koomey (2011), Koomey (2013), Pindyck (2017), and Rosen and Guenther (2015). Several of these authors and Stern (2016) decry widespread lack of representation of innovation processes across the economy, institutions, and human behavior. Koomey *et al* (2018) also make important suggestions to improve IAMs' outdated metrics and reporting formats.

[21] But not always. Despite its title's reference to 'energy system change,' van Sluisveld *et al* (2015) is *entirely* about supply: 'Demand-side investments are not taken into account as such estimates are subject to considerable uncertainty due to a lack of reliable statistics and definitional issues.' Yet they're more important to climate outcomes than are supply investments.

literature: e.g. Kriegler *et al* (2018) seem to assume no gains in *any* vehicles' efficiency other than from electrification). Even Grübler *et al*'s (2018) pioneering study appears to adopt integrative design only in buildings, not also in vehicles or industry (Lovins 2018), and its solar-power assumptions seem conservative.[22] So while these low-demand studies emphatically underline the importance of high-quality energy services in the 1.5 °C scientific and policy debate, they also show opportunities for significant further evolution in explicit demand-side technology analysis and in integrative design.

Table 1 (supplemental materials, part 3) usefully complements IPCC (2018) by comparing demand-side data for Grübler *et al* (2018) with other mitigation pathways that can also limit global warming to 1.5 °C but that entail higher demand and/or overshoot emphasizing active carbon removal. The exciting contrast emergent in table 1 is a starting-point for deeper exploration of more effective ways to meet growing energy service demand by using less energy more productively.

Another promising line of inquiry (Wilson *et al* 2018) observes that 'IAMs are neither designed to explore nor are useful for exploring the emergence of *novelty* in energy end-use.' That provocative paper illustrates a new framework called Disruptive Low-Carbon Innovation by 99 specific examples that 'combine business models and technologies to create appealing value propositions for consumers' and 'engage consumers in efforts to reduce emissions,' thereby both 'displacing carbon-intensive goods and services' and 'dislodging incumbent firms.' Integrative design shares similar attributes and outcomes.

Table 1, IPCC (2018), Wilson *et al* (2018), and the integrative-design discussion above powerfully expand the conversation on demand-centric solutions. The next frontier will be for an ambitious team to leapfrog over obsolescent, incremental efficiency supply curves[23] and consider best practices from and beyond efficiency's engineering literature. What might this reveal?

Findings of some overlooked national analyses

A tantalizing hint comes (Lovins 2018) from two book-length, independent, undisputed studies from respected institutions, each at a >30-analyst-year level of effort, both reported in peer-reviewed energy literature[24] but not yet noticed in the climate literature:

- A heavily documented and reviewed 2010–11 US study (Lovins and RMI 2011) by 61 RMI analysts showed how tripled energy productivity and quintupled renewables by 2050 could raise carbon productivity by 14–18-fold, save $5 trillion in NPV private internal cost (i.e. valuing carbon and all other externalities at zero, a conservatively low number), need no new inventions or national laws, and be led by business for profit. Its projections closely match actual 2011–18 GDP and primary and electric intensity, and understate renewable trends.
- A 2013–16 Chinese study (ERI 2017) led by the National Development and Reform Commission's noted Energy Research Institute in collaboration with Lawrence Berkeley National Laboratory, RMI, and Energy Foundation China showed with strong empirical grounding—and modeling widely considered the most thorough, rigorous, and economically explicit yet done for China—how a 7-fold increase in energy productivity and a 13-fold increase in carbon productivity by 2050 could save $3 trillion in NPV private internal cost. These findings strongly informed the 13th Five Year Plan now being executed.

If these exceptionally detailed findings for the top two global carbon-emitting nations, plus analogous EU ones, were simply extrapolated (scaled by GDP) to the other half of the world, they would imply that a 2 °C trajectory could cut the NPV cost of energy services by ~$18 trillion (ignoring all externalities). This crude thought-experiment (Lovins 2018) suggests that partial reinvestment in natural-systems carbon removal could probably achieve a ~1.5 °C trajectory, still with trillions of dollars left over.

Obviously such startling results merit detailed scrutiny and modeling. But these ambitious syntheses may prove conservative because they make only limited use of integrative design and of today's insights into urban form, human behavior, and further factors exploited by Grübler *et al* (2018) and in other advanced IAM literature cited above. Initial studies

[22] Grübler *et al* (2018)'s projection of solar PV adoption in 2020–30 is the industry's actual growth in the previous decade; Haegel *et al* (2017) show how global PV installed capacity could reach at least 3 TW by 2030 (15%/y CAGR) or 10 TW (29%/y); Grübler *et al* (2018) justify their 16%/y by their scenario's low demand. But their needed PV growth rate is actually lower anyhow, because their apparent 2020 base-year PV installed-capacity assumption from SSP2-1.9 is less (257 GW) than the actual 398 GW (BNEF says 418 GW) at the end of 2017, or roughly half of BNEF's actual 525 GW at the end of 2018.

[23] A note of caution: in principle, supply curves of the energy efficiency resource could greatly improve IAMs, but increasingly the supply-curve methodology too seems inadequate and outmoded. Technology-by-technology supply curves elucidate individual, incremental, isolated, small, easily analyzed subsets of the efficiency resource. They fail to capture systemic, holistic, integrative opportunities, and thus understate the efficiency resource. For example, traditional supply-curve analysis of buildings' energy efficiency considers incremental improvements in such components as insulation, glazings, air-tightening, and furnace and air-conditioner efficiency. But it doesn't capture the whole-building, passive-design optimizations that, as AR5 WG III Chapter 9's field data show, can keep the cost of artfully designed buildings' efficiency essentially flat for energy savings up to at least ~90%. Similarly in light-duty vehicles, both virtual designs and actual market offerings show that whole-vehicle integrative design can yield severalfold larger efficiency, at lower cost, than found by canonical measure-by-measure supply-curve analyses (Lovins 2018, 2018a, 2019b). Suggestive practical examples show the same in both heavy and high-tech industrial energy use (Lovins 2018).

[24] Lovins 2015, 2015a; Price *et al* 2017, Zhou *et al* 2016, and (a leading Chinese policy journal) Lovins *et al* 2016.

have already revealed (Mundaca et al 2019) 'an abundance of demand-side measures to limit warming to 1.5 °C…not all…"seen" or captured…and some insufficiently represented in the current policy discourse…, [so] demand-side mitigation in line with the 1.5 °C goal is possible' (though 'enormously challenging') and merits prompt investigation.

Innovative interventions

These opportunities transcend design and technology, and span many disciplines. The complexity of representing behavioral and lifestyle changes in IAMs (Schwanitz 2013, Mundaca et al 2019) retards understanding of policy-driven energy demand transformations—especially for policies not capturable via economic-engineering modeling (Mundaca Neij Worrell and McNeil 2010, Geels Berkhout and van Vuuren 2016). Comprehensive policy suites that complement traditional policy instruments and emphasize competitive and contagious diffusion of demand and skills can stimulate such successes as passive-building growth just in 2015–18, among Vancouver BC's <700 000 residents, from one to >2200 residential units and five other buildings, totaling 232 000 m^2, plus 2000 more units in the 2019 approvals pipeline.

Complementary non-price interventions are also gaining credence. For example, feedback on energy use boosts savings up to e.g. 15% (Karlin Zinger and Ford 2015), depending on feedback context and design (Abrahamse Steg Vlek and Rothengatter 2005). Using social norms to trigger comparison and competition helps too (Allcott and Mullainathan 2010), with due attention to potential side-effects (Andor and Fels 2018). Commitment devices, e.g. written pledges, and realistically self-imposed goals (Harding and Hsiaw 2014) also work, subject to methodological cautions (Andor and Fels 2018). At the risk of oversimplifying, policy assessments highlight that climate policies are likely to be more cost- and climate-effective when grounded in cognitive, motivational, and contextual factors that affect technology choice and use (de Coninck et al 2018). Welfare effects, long-term persistence of outcomes, causal mechanisms (e.g. psychological determinants), context-specific conditions, and how information is presented to heterogeneous energy users merit more attention. IAMs therefore should be complemented by evaluating decarbonization policies beyond economic incentives and technology criteria (Geels et al 2016, Mundaca et al 2019), especially outside the comfortable scope of utility-driven programs and experiments in developed countries (Hahn and Metcalfe 2016, Mundaca et al 2019).

Energy shrinkage—or rebound?

Efficient use and decarbonized supply are synergistic. Making clean energy supply replace, not just augment, fossil fuels needs efficient use to *reduce* demand so dirty, obsolete supplies exit the market. Thus in 1977–85, US GDP grew 27% while oil use fell 17%; today, speeding US coal retirements opens market space where renewables can compete (if not preempted by competition-free nuclear walled-garden zones (Lovins 2019c)). US electricity demand stopped growing a decade ago (Koomey 2019), about a decade later than primary energy (Lovins 2018c), but still-unbought efficiency costing one-tenth the average price of retail electricity could quadruple 2010 electric efficiency (Lovins and RMI 2011, p 204). For established reasons (Lovins 2018), savings so far typically only offset GDP growth, as in California, but coherent policy can tip electricity demand into shrinkage, as in Vermont. In 2000–17, 18 IEA member nations' electricity demand actually shrank, and averaging all 30 nations, its growth fell by four-fifths, from 1.6 to 0.3% yr^{-1} (IEA 2018c, p 28), all with nearly no integrative design.

Criticizing such counterfactuals based on unchanged intensities, some economic theorists claim that potential rebound effects (popularized by Owen 2010, *cf* Lovins 2011) will substantially reduce if not even reverse energy savings. In the complex literature of this evolving field, we give more weight to contrary evidence. Where observable, rebound is generally small (Greening et al 2000, Geller and Attali 2005, Sorrell 2007, Sorrell Dimitropoulos and Sommerville 2009, Goldstein et al 2011, Gillingham et al 2013, Gillingham et al 2015). Where included in major energy analyses, rebound's effects on energy demand proved immaterial (e.g. Lovins and RMI 2011). Early claims of >100% rebound or 'backfire' (efficiency's *raising* energy demand), based mainly on Saunders (2015), were severely criticized (e.g. Cullenward and Koomey 2015, 2016, 2016a, 2016b) but unpersuasively defended (Saunders 2017); credible observations of backfire, if any, are very rare, and backfire is theoretically dubious, empirically unprovable, and probably artifactual (Gillingham et al 2015). Grübler et al (2018) p 522 note examples of demand saturations that should blunt rebound; three decades' residential data (Lucon et al 2014) likewise seem inconsistent with substantial rebound. Rebound is in principle manageable by policy (e.g. taxing energy to hold energy-service cost roughly constant as efficiency rises, or replacing cheaper-to-run electric vehicles' lost fuel-tax revenues with road-use charges to fund upkeep), so IPCC (2018) p 137 found rebound 'should not be a distraction for policy inaction.' While energy efficiency is generally a macroeconomic stimulant, so too are many other actions (public health, education, female empowerment,…) that are not similarly criticized. And consumer choice theory implies that energy rebound enhances economic welfare—particularly for 'a zero-cost breakthrough rebound' (Gillingham Rapson and Wagner 2015) such as, we surmise, integrative design. Thus critics of efficiency based on rebound theories should be calling for greater energy efficiency (Goldstein Martinez and Roy 2011).

Sharply turning down the global thermostat

Complementing the CO_2 abatements discussed so far, another hopeful mitigation option emerges from the recent realization, reinforced by IEA (2017a), that a conceptual confusion—treating short-lived radiative forcing agents (CH_4, HFCs, O_3, and soot [black carbon]) as equivalent in kind to long-lived ones like CO_2—reflects a stock/flow confusion[25] that 'misrepresents…impact on global temperatures' (Allen *et al* 2018) and conceals a huge mitigation opportunity. Consider this analogy: If you're atherosclerotic and at long-term risk of heart attack or stroke, you should apply proven modalities like diet and exercise to slow or reverse plaque formation. But if you *also* happen to be hemorrhaging from a severed artery, don't waste time debating the equivalence factor between rate of blood loss and rate of plaque formation; stop the bleeding now. That will buy time—indeed, survival—to work on still-vital but slower remedies for your evolving chronic condition.

Similarly, debating whether to use 20 years (~86×) or 100 years (~34×) CH_4/CO_2 global-warming-potential-per-kg (not per molecule) equivalence factors—or even shorter, such as 120× over ~1.5 years (Muller and Muller 2017)—obscures a key insight. The roughly one-decade half-life[26] of exponentially decaying atmospheric CH_4 concentrates most of its climate threat in the early years after its emission—three-fourths in the first 17 y (*id*). This potent, ⩾60%-anthropogenic gas therefore offers exceptionally rapid climate leverage for good or ill, far disproportionate to its fractional contribution to marginal radiative forcing—a fraction often trivialized by terms like 'trace gases' and hence mistreated as a minor afterthought. Changing how we think and talk about the dynamics of methane in the atmosphere would be akin to discovering a small but useful emergency handbrake on our runaway carbon train: its prompt use alone can't stop the speeding train, but can markedly slow it down[27].

The importance of CH_4 abatement is concealed by equivalence factors but highlighted by dynamic simulation. For a given long-term temperature rise, the permissible budget for cumulative CO_2 release (a stock) can be offset by a permanent reduction at the *rate* at which CH_4 is emitted (a flow). MAGICC modeling by the International Energy Agency (IEA 2017a) reveals that abating just the *profitable* half of the oil and gas industries' intentional emissions from flares and engineered vents[28] could cut 2100 warming by 0.07 °C, *equivalent to avoiding 160 GT CO_2* over the rest of the century. IEA reckons this is roughly equivalent in 2100[29] warming effect to instant decarbonization today of all developed-country existing homes or all existing Chinese coal-fired power stations, or of half of all future automobiles worldwide. The expected financial returns, now being field-validated, probably often exceed those of hydrocarbon exploration and production, especially on a risk-adjusted basis. Assessments of this abatement opportunity may also benefit from some further industry insights on culture, technology, and business models that are often missing from academic discussions focused mainly on climate science.

Mitigating flares and vents typically requires bringing industry-standard 'safety process management' structures, practices, norms, behaviors, and cultures to the wellsite—historically exempted and often run by production firms unfamiliar with that sophisticated approach (born of caution because the business produces hot pressurized explosives). Major firms' expanding agreement to abate their own CH_4 emissions is a good start, but reflects a compliance mentality and subdued ambition. It overlooks much of the full business opportunity—conveniently concentrated mostly in a few

[25] I.e. 'for cumulative pollutants like CO_2, radiative forcing largely scales with the total stock (cumulative integral) of emissions to date, while for SLCPs [short-lived climate pollutants] like methane, it scales with the current flow (emissions rate) multiplied by the SLCP lifetime. The differing climate impacts of CO_2 and SLCP emissions become particularly problematic under ambitious mitigation. Falling SLCP emissions lead to falling global temperatures, while nominally "equivalent" CO_2 emissions…would incorrectly suggest that these falling emissions would cause further warming' (Allen *et al* 2018). Myhre *et al* (2013) confirm at p 711 that 'There is no scientific argument for selecting 100 years [for Global Warming Potential comparisons] compared with other choices…. The choice of time horizon is a value judgment because it depends on the relative weight assigned to effects at different times'.

[26] The perturbation life, reflecting complex atmospheric-chemistry effects, is a few years longer. Methane directly and indirectly caused about a third of 1750–2011 radiative forcing (Myhre *et al* 2013 figure 8.17), but its dynamics make it even more important on the margin.

[27] Seminal papers by Ramanathan and Feng (2008) and Ramanathan and Xu (2010) suggested early (and sustained) abatement of CH4 and CFCs in concert with aggressive CO_2 stabilization.

[28] Flares pass through ~2–10% of their CH_4 fuel unburned, depending on design, quality, maintenance, and windspeed. Engineered vents would normally be illegal for safety reasons, but are allowed if needed for safety, *e.g.* to relieve overpressure in a tank, even if that condition was deliberately designed in: such pressure relief valves can emit a puff of mixed hydrocarbons, including CH_4, tens or hundreds of times a day. Some systems also use old pneumatic controls that deliberately release gas. IEA (2017a p 412) found that within the oil and gas industries, 'The top 10% of emitting sources…contribute around 70% of total emissions,' and '…it has been suggested that…reducing emissions from super-emitters [across all supply-chain subsectors] to "normal" levels could reduce emissions by around 65–85%'. IEA estimates these industries' 2015 CH_4 emissions, probably conservatively (Saunois *et al* 2016), at ~76 MT—just under 60% intentional (vents), 35% fugitive (unintended leaks), and the rest from incomplete flare combustion. Nearly half the emissions are in Eurasia and the Middle East; two-thirds come from ten countries; ~55% are from gas operations. IEA's 2015 supply curve (2017a p 426) estimates that 75% abatement is technically feasible and 50% is profitable at 2015 or 40% at 2016 prices (or more at late-2018 prices), but the 50% average melds >60% profitable abatement potential in the oil industry with 40% in the gas industry.

[29] This is the normal benchmark year for Paris Agreement discussions. A nearer target date, such as 2050, would make CH_4 abatement more important and valuable.

thousand sites controlled by tens of companies in about ten nations. Compliance mindset needs to be supplanted by a gold rush to turn emissions into profits, whether executed by current operators or by new partners.

Oil and gas companies know how to contain CH_4 with virtual perfection, and routinely do so with sour gas, whose H_2S contaminant is more toxic than HCN, so leaking sour gas would kill many people. Though some of the largest firms are defending US methane standards from federal attack, most operators focus chiefly on producing valuable oil, not cheap gas. But three things are becoming clear: leaking sweet gas is toxic to the oil and gas *business*, endangering its license to operate (IEA 2017a); abating just ~10–25 MT yr^{-1} of CH_4 *could stabilize the entire global CH_4 cycle*; and abating even more to *reduce* atmospheric CH_4 concentrations could create both profits and heroes. Combining these insights, *any* supermajor or large oilfield service company could use its extraordinary technical and organizational skills to try launching a quick rollup of this global opportunity to offset large marginal CO_2 emissions and help buy time to abate the rest[30]. Field trials of profitable flare-and-vent abatement (usually selling microfractionator-separated C_1–C_5 alkanes into nearby infrastructure or local LPG markets), and outreach to leaders of supermajors capable of saving their own business and their customers' habitat, have begun. Let the competition roll.

Similar efforts in natural-systems agriculture, abating coal-mine vents (especially in China), and rapidly abating non-CH_4 'super-emitters' are still young but need greater force and urgency. In a strong precedent, Xu and Ramanathan (2017) find that sustained 'maximum deployment of current technologies' to abate all four super-emitters is worth 'about 0.6 °C by 2050 and 1.2 °C by 2100.' Proving the power of this approach, the Montréal Protocol's phaseout of O_3-depleting halocarbons and the like has *already* abated >200 $GTCO_{2e}$—'many more times more than international *climate* agreements to date' (Clare 2018). Astute engagement with hydrocarbon operators to shift from compliance to entrepreneurial mentality and from their own emissions to everyone's could build on that success.

Conclusions

This paper points out that recent developments in energy markets and analyses may open new prospects for the achievability, social/economic acceptability, and economic attractiveness of climate targets in the Paris Agreement, including its aspirational 1.5 °C cap. A renewed and coordinated effort to represent these developments in influential global climate and energy systems models is critical to saving trillions of dollars while achieving stringent climate mitigation outcomes.

The paper first describes the unexpectedly dynamic recent uptake of renewable energy, then summarizes overlooked recent progress in and future potential for advanced end-use energy efficiency. These two classes of resources have already markedly shrunk the gap between pre-2010 implementation rates and those needed to achieve targets indicated by the climate modeling literature. Many models, using 'historic' trends, consider 1.5%–2% yr^{-1} drops in primary energy intensity to be ambitious; yet the 2010–18 rate averaged 2.03% yr^{-1}, even reaching 2.7% yr^{-1} in 2015, and could rise further. Reduced primary energy intensity *plus* increased share of decarbonized final supply have lately matched the sustained ~3.4% yr^{-1} that IPCC AR5 found necessary for a 2 °C trajectory. Together they are only half of, but trending toward, the sustained ~6.7% yr^{-1} needed for 1.5 °C.

From these observations emerge some respectful suggestions for future modeling efforts: there is a need to reconsider use of pre-2011 energy data and to better comprehend and apply modern energy efficiency options from advanced practitioners and their underapplied engineering-based literature. IAMs' efficiency deficit needs a careful look in balance-of-effort, methods, depth, breadth, and ability to model integrated/systemic measures and increasing returns (whose absence greatly understated renewable growth). There is also an opportunity to critically acknowledge, study, test, and if warranted apply high-quality work from other disciplines: cross-fertilization with different perspectives and schools of thought beyond technocracy can often yield step-changes in enriching analytical insights. Models confirm the scope for ambitious mitigation pathways, and provide an important platform to inform emitting industries, policymakers, and the public about rapidly exploiting both modern energy efficiency and the short atmospheric lifetimes of CH_4 and other super-emitters. Enhanced, more complementary ways of abating these concentrated emissions and exploiting nonlinear benefits (Houser 2018, Farmer *et al* 2019, Lovins 2019) can capture new business and socio-political opportunities by applying basic first-aid principles to our planet's ailing climate.

In conclusion, when the mainstream climate models integrate these methodological advances and new evidence, they are likely to recalibrate the prospects for achieving ambitious climate targets, including 1.5 °C. The IPCC's *Special Report on 1.5 °C Global Warming* (2018, p 15) finds the needed 'systems transitions… unprecedented in terms of scale, but not necessarily in terms of speed, [needing]…deep emissions reductions in all sectors and a wide portfolio of mitigation options'—without yet alluding to encouraging recent precedents in rates of emission reductions and in today's large-scale system transitions. Further capturing efficiency resources may help achieve the 1.5 °C target using less or no bio-energy with carbon capture and storage (BECCS) in P2–P4 of the illustrative scenarios in the report (see IPCC 2018's SPM3b) or with less need for

[30] However, multiple studies emphasize that abating CH_4 and other short-lived emitters complements and helps risk-hedge, but cannot delay or replace, stringent CO_2 abatement: Pierrehumbert 2014, Myhre *et al* 2011, Rogelj *et al* 2014. That is, abating CH_4 potentiates simultaneous CO_2 reductions but does not permit their postponement.

an immediate plunge in demand as in P1. Such changes may improve the scenarios' institutional, socio-cultural, and environmental/ecological feasibility as well as the balance of their net trade-offs and synergies with SDGs and other development and environmental agendas—thus recalibrating climate prospects for all.

Finally, none of the rich menu of climate-change mitigations—whether driven by business, public policy, or civil society and individual choice—need wait for these modeling improvements, but all would benefit from them, just as IAMs have heightened appreciation of health co-benefits (West *et al* 2013, Thompson *et al* 2014). The technical evidence is now clear that climate mitigations well in excess of those traditionally modeled will make sense, make money, create immense co-benefits (chiefly for development, equity, health, and security), and help abate climate change. Refined modeling therefore need not precede but should evolve in parallel with ambitious policy interventions and aggressive adoption.

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