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EDITORIAL

How big is the energy efficiency resource?

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Abstract

Most economic theorists assume that energy efficiency—the biggest global provider of energy services—is a limited and dwindling resource whose price- and policy-driven adoption will inevitably deplete its potential and raise its cost. Influenced by that theoretical construct, most traditional analysts and deployers of energy efficiency see and exploit only a modest fraction of the worthwhile efficiency resource, saving less and paying more than they should. Yet empirically, modern energy efficiency is, and shows every sign of durably remaining, an expanding-quantity, declining-cost resource. Its adoption is constrained by major but correctable market failures and increasingly motivated by positive externalities. Most importantly, in both newbuild and retrofit applications, its quantity is severalfold larger and its cost lower than most in the energy and climate communities realize. The efficiency resource far exceeds the sum of savings by individual technologies because artfully choosing, combining, sequencing, and timing fewer and simpler technologies can save more energy at lower cost than deploying more and fancier but dis-integrated and randomly timed technologies. Such 'integrative design' is not yet widely known or applied, and can seem difficult because it is simple, but is well proven, rapidly evolving, and gradually spreading. Yet the same economic models that could not predict the renewable energy revolution also ignore integrative design and hence cannot recognize most of the efficiency resource or reserves. This analytic gap makes climate-change mitigation look harder and costlier than it really is, diverting attention and investment to inferior options. With energy efficiency as its cornerstone and needing its pace redoubled, climate protection depends critically on seeing and deploying the entire efficiency resource. This requires focusing less on individual technologies than on whole systems (buildings, factories, vehicles, and the larger systems embedding them), and replacing theoretical assumptions about efficiency's diminishing returns with practitioners' empirical evidence of expanding returns.

1. Introduction

In theory, theory and practice are the same, but in practice they are not. Most climate modelers explicitly or tacitly use economic theory as the dominant framework for assessing potential technological gains in energy end-use efficiency (Lovins 2018a)[1]. Economic theory tends to treat energy efficiency as a limited and dwindling Ricardian resource (like fuels) whose adoption, driven by policy and price, will deplete its potential and raise its cost. Yet as a four-decade global field practitioner of advanced energy efficiency in all sectors, I consistently observe the opposite. Energy efficiency is empirically an expanding-quantity, declining-cost resource. Its adoption is increasingly motivated by positive externalities but constrained by strong, diverse, complex, and challenging market failures requiring both policy intervention and business innovation (Hirst and Brown 1990, Koomey 1990, Sutherland 1991, Lovins 1992, Koomey *et al* 1996, Bressand *et al* 2007, Metz *et al* 2007 pp 418–430, Gillingham *et al* 2009, Granade *et al* 2009, National Academies 2009b section 2.7). Those barriers can seem homeostatic: low ambitions and limited barrier-busting efforts yield meager progress that seem to justify inaction, while high ambitions and efforts yield impressive results that reinforce doubling down. But the lively debates about how to turn obstacles into business opportunities, and

[1] This Essay uses 'efficiency' in the engineering sense (ratio of energy output to energy input, or of effect to effort), not in the economic sense. There are seven kinds. 'End-use efficiency' measures how much of the energy delivered to a customer is converted to end-use services (comfort, illumination, mobility, torque, etc). Further upstream, 'extraction efficiency' is from fuels in the ground to raw primary fuels; 'conversion efficiency' is thence to secondary energy (gasoline, electricity, etc); 'primary efficiency' is from primary fuels or renewable flows to customer delivery; and 'distribution efficiency' is from conversion (in a refinery, gas processing plant, power station, etc) to customer delivery. Further downstream, 'hedonic efficiency' is from delivered service to economic welfare and human well-being. 'System efficiency' spans the whole range from energy resources to welfare and well-being—from ultimate means to ultimate ends. This discussion focuses on efficiency gains from end-use technology, not from behavior, urban form, etc. It uses energy 'savings' as simplified, if sloppy, shorthand for reduced energy intensity.

how much the externalities are worth, miss a crucial point that could raise ambition and ignite decisive action: *the efficiency resource itself, and its economically capturable 'reserves,' are severalfold larger and cheaper than the energy, business, economics, policy, and climate communities commonly acknowledge.*

Most traditional analysts and deployers of energy efficiency see and use only a modest fraction of the worthwhile efficiency resource. In the language of the oilpatch—formally, of economic geology (United States Geological Survey 1991)—they count only demonstrated and measured (proven) reserves; often omit subeconomic demonstrated resources without symmetrically competing them against long-run marginal supply; and usually omit indicated and inferred reserves and undiscovered and hypothetical resources. In energy efficiency as in geology, total reserves exceed proven reserves, and the resource base, increasingly exploitable as exploration and extraction techniques improve, far exceeds both.

This geological analogy is useful for quantity but misleading for cost, because unlike orebodies, most omitted energy efficiency resources cost *less* than those now being exploited, so adding them would *de*crease average cost and speed adoption. That is because their extra savings come not from using more or fancier widgets (Regnier 2017), but from artfully choosing, combining, sequencing, and timing *fewer and simpler* widgets to achieve bigger savings and more co-benefits[2] at lower cost. Reserves are the profitably exploitable subset of resources, so 'discovering' larger but cheaper efficiency resources disproportionally increases reserves. Moreover, the technical progress that keeps making oil (Lovins 2014) and other minerals cheaper to extract applies comparably if not more to energy efficiency, stranding more competing assets sooner.

Such 'integrative design' of buildings, appliances, equipment, vehicles, and industrial processes has been independently validated[3] (Brohard *et al* 1998, Lucon, Ürge-Vorsatz *et al* 2014), but is poorly reflected in most literature and education in energy engineering, and is virtually absent from economic thought and literature, because it reflects insights available only from practical design experience. The missing majority of efficiency reserves and resources thus continues to hide in plain view. Oil deposits and orebodies are finite assemblages of atoms; mining and dispersion deplete their negentropy. But energy efficiency resources are infinitely[4] expandable assemblages of *ideas* that deplete nothing but stupidity—a very abundant if not expanding resource.

This conceptual gap has serious consequences. Overlooking most of the energy efficiency potential gravely understates the scope for profitable climate solutions: it makes climate protection look harder and costlier than it actually is, diverting and inflating attention to costlier and riskier options. The examples below suggest that such misallocation of scarce resources—money, effort, skills, focus, time—overlooks more than half of the modern energy revolution, reinforcing most climate models' bias toward the supply side and sketchy treatment of the demand side (Lovins 2018a) and thus further suppressing efficiency's full capture. This is analogous to, and probably as important as, underplaying noneconomic-social-science factors, such as behavior and urban design, in discussions dominated by technologists (Creutzig *et al* 2016, 2018, Mundeco, Ürge-Vorsatz and Wilson 2018).

Few policymakers realize that saved energy is already the world's largest source of energy services, bigger than oil (i.e., 1990–2016 reductions in global energy intensity saved more energy in 2016 than the oil burned in 2016). The public's impression is similarly lopsided. Decreased energy intensity during 1975–2016 saved 30× more cumulative US primary energy than doubled renewable production supplied, yet the ratio of headlines seems roughly the opposite, because renewables are conspicuous but unused energy is invisible. Far greater savings available from integrative design are almost unimaginable.

Even for most engineers—whose profession has improved efficiency for millennia—integrative design was not in their textbooks or courses[5] and remains absent from their otherwise admirable practice. No one disputes that if components are not designed to work with each other, they will work against each other, making savings *less* than the sum of the parts, but the reality that achieving exactly the opposite is practical and profitable, given a different design

[2] In buildings, these are often worth an order of magnitude (sometimes two) more than saved energy costs (Ürge-Vorsatz *et al* 2014, Muldavin 2010, Bendewald *et al* 2014, Bendewald Miller Muldavin 2015). Large co-benefits are also common in industry (Worrell *et al* 2003, IEA 2010, Williams *et al* 2012) and vehicles (Cramer and Lovins 2004).

[3] Just the author's organization's empirically grounded practice has integratively redesigned >1000 buildings, scores of major industrial facilities worth over $40 billion, and various land and sea vehicles.

[4] Energy efficiency is limited by the laws of thermodynamics, but by one global estimate, 2005 global Second Law efficiency (AIP 1975) of energy conversion systems was only ~11% (Cullen and Allwood 2011), i.e., energy use was 9× the theoretical minimum, so including also passive systems, '85% of energy demand could be practically avoided using current knowledge and available technologies' (Cullen *et al* 2011). (Composition of usage matters too: during 1900–98, each US electric end-use became more efficient in Second Law terms, but overall use of electricity did not, because an increasing share was used for low-temperature heat (Ayres *et al* 2005).) Integrative design can be thought of either as a way to increase First Law efficiency or as a way to approach Second Law limits more closely and at far lower cost. Moreover, apparent thermodynamic limits can often be evaded by redefining the desired changes of state: rather than just improving lighting equipment, you can open the curtain to admit daylight, and rather than making kilns more efficient for producing ceramics, you can substitute superior but nearly zero-energy materials made by techniques observed in nature and imitated by biomimetic design (Benyus 1997).

[5] With a few exceptions (Lovins 2007, 2011, Stasinopoulos *et al* 2009, Autodesk 2011). Rocky Mountain Institute aims to remedy this lack; is exploring diverse ways to scale integrative design so it becomes common, not rare; is refining and testing detailed pedagogy; and solicits case-studies and other suggestions.

method and process, remains strangely hard to recognize. Design is seldom recognized as a scaling vector—a way to get big fast—and because it is not a technology (the framework in which energy efficiency is conventionally organized), it remains rare in taxonomies and agendas of energy efficiency opportunities. Canonical studies of the quantity and cost of potential energy efficiency gains (e.g. Blok 2004, Bressand *et al* 2007, Stern 2007, International Energy Agency 2008, Graus *et al* 2009, National Academies 2009a, 2009b) sometimes mention but do not adopt integrative design potential[6]. IPCC's Fifth Assessment applies it only to buildings (Edenhofer *et al* eds., ch 9), and with scant effect so far on the climate models IPCC uses.

1.1. Urgency of scaling integrative design

As Blok (2004) reminds us, Rosenfeld and Bassett (1999) pointed out that energy efficiency gains have internal dynamics. The ~3% yr^{-1} historic US intensity reductions, or ~2% yr^{-1} for technical efficiency without structural change, can be interpreted not simply as aggregated improvement in the total stock of energy-using devices and systems, but as a ~5% yr^{-1} improvement in *new* equipment's efficiency (~3.5% yr^{-1} globally). Efforts should therefore include not just higher specific efficiency for energy-using equipment, but also faster turnover (the net effects of replacement, addition, and retirement) and premature scrappage of the worst units. Blok (2004) shows that ~5% yr^{-1} gains in the specific efficiency of new OECD equipment can plausibly continue *for as much as another half-century*. In both newbuild and retrofit, integrative design can increase ambitions and achievements in both specific efficiency *and* turnover speed, because it can shorten and simplify construction, deliver superior services, and create valuable co-benefits. Conversely, standard dis-integrated design often complicates or blocks integrative design, making it hard and costly to achieve later. Thus faster deployment of conventional energy efficiency will create more lost opportunities for bigger and cheaper savings—unless integrative design is simultaneously spread, deepened, and scaled.

This is most important in countries rapidly building infrastructure, where efficiency opportunities lost now can lock in wasteful energy use for decades. As IEA member nations' absolute energy use shrinks from its 2007 peak, developing countries' rising share of global energy use offers important opportunities to leapfrog to the best technologies, in which they could even seek and achieve market dominance, *and* to adopt integrative design. Integrative/passive design is the largest element of China's buildings-efficiency potential (Zhou *et al* 2016). Thereby saving 70%–90% promptly avoids the risk of saving 20%–40% with shallow early retrofits that may preclude 70%–90% deep-retrofit savings later, so waiting until the deep savings are readily available may save more energy over the long run than rushing into shallow retrofits (Güneralp *et al* 2017); happily, China can probably achieve goals equally aggressive in depth and pace. (The whole economy is more complex but equally ripe in opportunity: China's world-leading intensity reductions owe much to higher initial intensity, an earlier stage of deep structural change, and the greater ease of building things right than fixing them later.) India, with even more people but still-low car ownership, likewise aims to head off private-car dominance by leapfrogging to shared, connected, electric personal mobility by 2030 (NITI Aayog and RMI 2017). Encouragingly, China and India are eager to adopt integrative design for both new and retrofit applications. And unlike most purely technological options, integratively designed buildings tend to draw on traditional culture, support mindful behaviors and lifestyles, and sustain health, equity, security, economic value, and other major co-benefits (Lucon, Ürge-Vorsatz *et al* 2014, pp 705–709).

It is long past time for efficiency assessments to include integrative design. Most analysts now acknowledge that solar and windpower can far surpass traditional predictions based on historic trends (Creutzig *et al* 2017, Breyer *et al* 2016) and can achieve expanding returns: buying more modern renewables makes them cheaper, boosting their sales in a virtuous spiral. Now the same realizations are overdue for energy efficiency—persistently the largest (IEA 2017), 'least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services' (Lovins 2005), and offering expanding returns not just through mass-produced widgets but also by substituting brains and information for hardware.

Thus energy efficiency is not a limited and dwindling resource as most economic theorists assume, but the expanding-quantity, declining-cost resource that advanced practitioners observe. This Editorial will therefore challenge traditional assessments of how much energy can be saved by technical improvements in end-use devices and systems, and will suggest implications and next steps.

[6] For example, the National Academies' latest US energy synthesis (2009a) mentions at pp 144–145 how a 'technology-by-technology approach…misses the kinds of integrated measures that can be identified with the whole-building approach,' but its estimates of efficiency potential include no integration. Its underlying efficiency analysis (2009b) devotes section 2.4.1 to 'Integrated Whole-Building or System-Wide Approach' (pp 40–41) and further explains their application (pp 54–57), described for at least commercial buildings as 'a huge opportunity for improved energy performance using existing, available technologies' from '*integrated design*…a transformation not in technology but in conceptual thinking about how building systems can most effectively work together, and successful implementation of design intent.' However, the key economic insight—that integrative design generally shrinks or eliminates costly mechanical systems and other cost drivers, often by enough pay for the efficiency measures—is missing; the whole discussion does not affect the study's findings about potential savings and their costs even in buildings; integrative design is not considered at all for vehicles or industry; and customary dis-integrated design is not noted as an obstacle, though Rosenfeld (1999) had noted his surprise not that the ACT[2] experiment he and I helped co-lead achieved such large savings (Brohard *et al* 1998), but that it was so hard to find designers competent to do so.

2. Examples of overlooked efficiency resources

An IPCC Working Group III panel co-led by Dr Mark Levine of Lawrence Berkeley National Laboratory nicely summarized integrative design's least underused application—in buildings (Metz *et al* 2007, p 416), which use one-third of global final energy and nearly three-fourths of US electricity:

> *Energy and cost savings through use of the Integrated Design Process.* Despite the usefulness of supply curves for policy-making, the methods used to create them rarely consider buildings as integrated systems; instead, they focus on the energy savings potential of incremental improvements to individual energy-using devices.…[I]ntegrated building design not only can generate savings that are greater than achievable through individual measures, but can also improve cost-effectiveness. This suggests that studies relying solely on component estimates may underestimate the abatement potential or overestimate the costs, compared with a systems approach to building energy efficiency. Recent published analyses show that, with an integrated approach, (i) the cost of saving energy can go down as the amount of energy saved goes up, and (ii) highly energy-efficient buildings can cost less than buildings built according to the standard practice (Harvey 2006, chapter 13).

Eleven years later, no mainstream literature or official study acknowledges that this is true not just of buildings but also of vehicles and of industrial processes and equipment—hence virtually all energy-using devices. Not only do 'public institutions, policies and financial resources pervasively privilege energy-supply technologies,' so 'Directed innovation efforts are strikingly misaligned with the needs of an emissions-constrained world' (Wilson *et al* 2012), but the same factors privilege technology over design and hardware over thought, thus greatly understating what good design can do, and where.

2.1. Buildings

A well-known example is the 2010 retrofit of the Empire State Building (United States Green Building Council 2008, Buhayar 2009, Harrington and Carmichael 2009, Vaughn 2012, Empire State Building 2014) after it was separately retrofitted from single to double glazing, making further savings harder and costlier. The integratively designed whole-building retrofit still cut site energy use 38%, from 277 kWh m^{-2} yr^{-1} (slightly below the US office median of 293) to 173 kWh m^{-2} yr^{-1}. Most of the efficiency gains were paid for by \$17.4 million capital savings from making the cooling systems one-third smaller to match the reduced cooling load, rather than replacing them with larger new ones (plus bigger electrical risers). This downsizing cut simple payback to 3 yr (<1 yr counting benefits to the landlord or tenants). Dis-integrated design had predicted the same payback for 6× smaller savings.

Three years later, an even deeper retrofit of Denver's Byron Rogers Federal Center from 284 to 85 kWh m^{-2} yr^{-1} cost-effectively saved 70% (RMI 2012, Bartels and Swanson 2016), making that difficult half-century-old building more efficient than the then-best *new* US office (NREL's Golden [Colorado] RSF office, 108 kWh m^{-2} yr^{-1}, Hootman *et al* 2012). That in turn is less than half as efficient as RMI's 2015 passive, no-boilers, no-chillers, net-positive, 51 kWh m^{-2} yr^{-1} Innovation Center in Basalt, Colorado's even colder climate[7]. A Bavarian building, though not just an office, reportedly uses three-fifths less yet—just 21 kWh m^{-2} yr^{-1} (Meyer 2015, Passive House Database 2013). Yet all the needed technologies existed over a decade ago: the best US office efficiency, both new and retrofit, roughly doubled in five years not through better technology but through integrative *design* (Lovins 2007, 2010): not by adding more widgets, but by leaving more out.

2.1.1. Choosing and combining technologies

Saving capital cost by shrinking or eliminating heating, ventilation, and air-conditioning (HVAC) equipment to pay for the efficiency gains that displace that equipment (Metz *et al* 2007, p 389) was established long ago in new buildings. For example, a 1983 passive house, office, and indoor farm at 2200 m elevation near Aspen, Colorado, where temperatures could then dip as low as –44 °C and 39 days' continuous midwinter cloud had occurred, saved ~99% of its space-heating energy at ~\$1100 *lower* construction cost by eliminating the heating system (RMI (Rocky Mountain Institute) 2007, Yi *et al* 2010, Knapp 2018). In Europe alone by 2012, ~57 000 passive house-standard buildings totaling 25 Mm^2 had similarly eliminated their space-heating needs at modest marginal construction costs, especially with experienced designers and builders and in commercial buildings (Lucon, Ürge-Vorsatz *et al* 2014); recent estimates exceed 160 000. Harvey (2013) finds:

> The additional costs of meeting the passive standard for heating loads in new buildings, which represents a factor of 5–10 reduction of heating load compared to current standard practice, have ranged from 0% to 16% of the construction costs of reference buildings. High performance

[7] The most efficient in the coldest US climate zone (RMI 2016 and its citations), using 51 gross kWh m^{-2} yr^{-1}, one-sixth normal, still declining with further commissioning. Solar-electric production exceeds usage.

> commercial buildings, with overall energy intensities of 25%–50% that of recent conventional buildings, have been built at less cost, or only at a few percent more cost, than conventional buildings.

Practice has since improved so rapidly that the Energiesprong (2018) industrialized deep-retrofit/renovation method, spreading from Europe to North America (RMI 2017c), can convert many ordinary old dwellings to 30-y-warranted Net Zero Energy performance, financed by energy savings without subsidy. As IPCC confirms (Lucon, Ürge-Vorsatz *et al* 2014, pp 702–704), deep retrofits can have lower lifecycle costs than shallow retrofits (Korytarova and Ürge-Vorsatz 2012), contrary to economic theory, and 'very high performance new construction can be achieved at little, or occasionally even at negative, additional costs.' Germany's strategy for decarbonizing its buildings by 2050 through deep retrofits and PassivHaus newbuilds finds much lower total lifecycle cost of ownership than running and fixing buildings incrementally, and confirms that deep retrofits have about the same lifecycle cost as shallow ones (Umweltbundesamt 2017).

In perhaps the most convincing terse meta-analysis of international best evidence, drawn from eight compilations published during 2006–13, IPCC's AR5 Working Group III found (figure 1) that superefficient new and retrofitted buildings need not raise construction cost until energy savings reach at least ~80%–90% if then.

Some costs shown in both graphs are indeed much higher, so analysts unduly influenced by economic theory might fit a rising supply-cost curve to these datasets. But an insightful and ambitious practitioner would instead diagnose the vertical scatter as reflecting highly inconsistent design and installation skills, and would therefore aim to improve the higher-cost outcomes to converge to the least-cost projects' practices. Whatever exists is possible. Inferior practice is to be improved or competed out, not imitated as inevitable.

Hot-climate results are similar. A new tract house in Davis, California, with no air conditioner or furnace was designed in 1994 to save 82% of the energy allowed by the then-strictest US standard (1992 California Title 24). It delivered superior thermal comfort, yet if built in quantity, would have cost ~\$1800 less than normal to build and ~\$1600 less in present value to maintain (Lovins 1995, Pacific Gas and Electric Company 1990–97). That 45 °C-peak site, and the same ACT[2] experiment's (Brohard *et al* 1998, Pacific Gas and Electric Company 1990–97) 46 °C-peak Stanford Ranch house, reconfirmed that all-passive dry-climate cooling can cost the same or less to build. Even in sweltering Bangkok, Professor Suntoorn Boonyatikarn's 350 m^2 1996 house, adapting the near-Aspen house's 1983 integrative design to the opposite climate, delivered superior comfort with ~10% of normal air-conditioning energy at normal construction cost (Lovins 2008). Those two houses span the subarctic-to-tropical range of the Earth's inhabited climates. In large hot/wet-climate buildings, 1.5 million m^2 of well-known Infosys offices in six Indian cities use one-fifth the normal amount of energy (as little as 66 $kWh\ m^{-2}\ yr^{-1}$) to deliver superior comfort at ~10%–20% lower capital cost (R Parikh, personal communications, 2012–18, Slavin 2014). Zimbabwe's largest office and shopping complex, the 31 600 m^2 1996 Eastgate Centre in Harare, uses biomimetic passive cooling and ventilation design (modeled on termite mounds) to save 90% of mechanical energy and deliver normal or better comfort at normal construction cost (Doan 2012).

Overall, therefore, integrative design makes order-of-magnitude building efficiency improvements inexpensive (or even cheaper than normal), mainly by eliminating or shrinking and simplifying HVAC equipment. This enables total demand reductions around 4–6×, not the usual <2×, thus expanding cost-effective energy savings by ⩾2×. But deeper design integration can make this opportunity even larger and cheaper, as we explore next.

2.1.2. Sequencing technologies

Major building systems and functions often reveal hidden opportunities to do the right things *in the right order* and thus save even more energy at lower cost. For example, more-efficient lighting equipment like LEDs is only the sixth priority in the steps recommended in the Illuminating Engineering Society's *Handbook of Fundamentals*. Starting with the usually ignored first five steps[8] saves far more lighting energy (>90%), works better, and often costs less by reducing the amount and complexity of equipment. In typical offices, this approach can reduce the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) 90.1–2007 nominal lighting power density by ~4–10×—the range depending on daylighting—with the same or better visibility and esthetics.

Similarly, more efficient air-conditioners or chillers are the sixth priority among space-cooling options described in the ASHRAE's *Handbook of Fundamentals*. Starting with the first five[9], four of which are widely ignored,

[8] Improve the visual quality of the task; improve the cavity reflectance and geometry of the space; improve lighting quality to cut veiling reflections and discomfort glare; optimize lighting quantity; harvest and distribute natural light; and then, after raising source efficacy, optimize luminaires and improve controls, maintenance, and training.

[9] Cool the people, not the building; exploit all comfort variables to expand the range of conditions in which people feel comfortable; minimize unwanted gains of heat and humidity into the space; passive cooling (ventilative, radiative, ground—or groundwater-coupling, etc —Cook 1989); active nonrefrigerative cooling (evaporative, desiccant, absorption, adsorption, hybrids such as Pennington and van Zyl cycles); superefficient refrigerative cooling; and coolth storage and controls (Houghton *et al* 1992, Shepard *et al* 1995). Using just a subset of the first four methods, many traditional passive designs offer no-HVAC hot-climate comfort, such as Kerala's homes with 23 °C–29 °C bedroom temperatures despite ambient daily ranges 17 °C–36 °C (Lucon and Ürge-Vorsatz *et al* 2014 p 693), or Dhiru Thadani AIA's modern convective-double-wall apartment blocks, which sustain 11 C°–12 C° lower interior temperatures through the Mumbai monsoon, can gain a further 5 C° comfort range (7 C° with optimized air-velocity fluctuations) from a ceiling fan, cost 2% more to build, and had excellent market reception for 2 Mm^2 built.

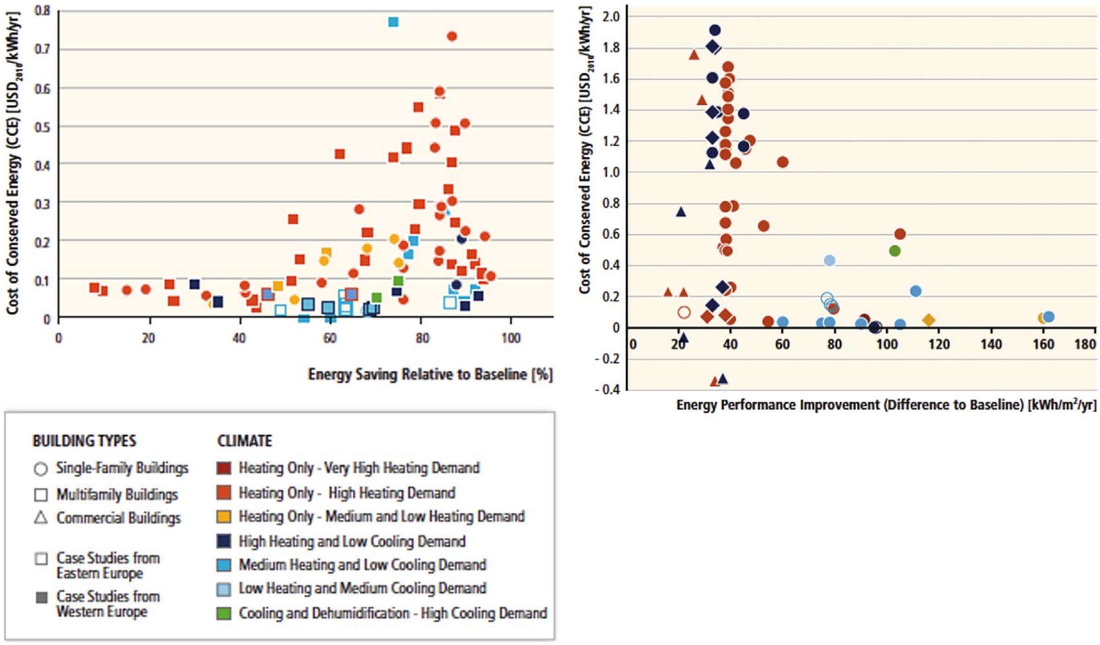

Figure 1. New (left) and retrofitted (right) buildings of diverse types and climates can achieve ~90% energy savings without requiring material if any greater construction cost (Lucon, Ürge-Vorsatz *et al* 2014, pp 702–704), assuming a 3% yr^{-1} real discount rate and building lives of 40 yr for newbuilds and 30 yr for retrofits. Figures reproduced by permission from O Lucon, D Ürge-Vorsatz, A Zain Ahmed, H Akbari, P Bertoldi, L F Cabeza, N Eyre, A Gadgil, L D D Harvey, Y Jiang, E Liphoto, S Mirasgedis, S Murakami, J Parikh, C Pyke, and M V Vilariño, 2014: Buildings *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Ed O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, K Seyboth, A Adler, I Baum, S Brunner, P Eickemeier, B Kriemann, J Savolainen, S Schlömer, C von Stechow, T Zwickel and J C Minx (Cambridge: Cambridge University Press).

can provide better thermal comfort at lower capital cost in any climate—using *no* refrigerative air-conditioning—saving equipment, hence capital cost, and ~90%–100% of cooling energy. This can make even lower cost, tripled-efficiency refrigerative systems uncompetitive and unneeded (Houghton *et al* 1992, Shepard *et al* 1995). And the motor systems that drive HVAC equipment have analogous potential, as noted below[10].

2.1.3. Timing technologies

The capital savings from shrinking or eliminating HVAC equipment in new buildings can also be largely obtained in retrofits by *timing* deep retrofits to match routine major renovations, such as renewing HVAC systems or façades. Thus a retrofit design for a 18 606 m^2 all-glass Chicago office tower, needed because of normal seal failures in its curtainwall, found 76% energy-saving potential at slightly *lower* construction cost than routine 20 y reglazing that saves nothing. The retrofit's 4× smaller cooling load, hence an HVAC system 4× smaller but 3.8× more efficient, would need ~$200 000 less investment than normal HVAC renovation—slightly more than enough to buy the other improvements, equivalent to a –5 month payback (Lovins 1995). This design was approved by the owner but not executed because the property was controlled by a cash-short leasing broker incentivized on dealflow and unwilling to delay commissions from lease renewals—which then failed, so the building was sold at a steep discount and the opportunity was lost for another two decades. This illustrates the complexity of the >20-link commercial real-estate value chain and the pervasive perversity of its incentives (Lovins 1992)—each of which can be corrected, creating a business opportunity, but each of which can be a showstopper if ignored. Nonetheless, mindful portfolio owners can use available tools to coordinate their buildings' deep retrofits (RMI 2017a) with planned major building events like HVAC and glazing renewals (RMI 2017b), turning a potentially unproductive renovation cost into a roughly zero or negative cost while creating huge property value.

Such building examples generally apply advanced glazings that insulate better, look clear, pass abundant daylight, but block unwanted heat transfer, and are spectrally 'tuned' to each direction. Optimizing lighting, daylighting, airflow, heat transfer, and many other factors, these projects closely integrate diverse design and construction skills by finding the right designers,

[10] So do many plug loads, appliances, and thermal systems. For example, the ACT^2 Davis House designers specified a water-cooled refrigerator—boosting its efficiency, getting free water-heating, and turning the refrigerator into a summer space-cooling device because the hot water goes down the drain, taking unwanted room heat with it. RMI's Innovation Center likewise heats water with an air-to-water heat pump capturing waste heat from its IT equipment, air-to-air heat-exchanger fan-motors, and solar inverters. Large buildings and factories often have important opportunities for thermal integration, cascading heat to lower-quality uses, especially with today's COP 6–15 low-lift heat pumps ($\Delta T = 13-31$K, Gasser *et al* 2017). And urban form can powerfully reinforce building efficiency (Creutzig *et al* 2015, Güneralp *et al* 2017).

organizing them in the right way, and preferably rewarding them for savings, not for expenditures (Eubank Browning 2004, Bendewald *et al* 2010, RMI 2016). Some examples (e.g. RMI (Rocky Mountain Institute) 2007) have far deeper layers of design integration, with elements that perform as many as 8–12 diverse functions but have only one cost.

Integrative design in buildings—new and old, big and small, in all climates—is no longer as novel as when it was described by Working Group III of the IPCC's Fourth Assessment Report (Metz *et al* 2007). By 2014, the Fifth Assessment Report's chapter 9 documented many examples of roughly zero-net-cost superefficient buildings with diverse sizes, programs, and climates (Lucon, Ürge-Vorsatz *et al* 2014, ch 9; figure 1 above), and explained how interactions and simplifications in their design can offset higher component costs (p 689). However, its chapters 8 and 10 did not apply this approach to vehicles, industry, nor to the systems within and outside them. The following examples briefly illustrate such opportunities.

2.2. Mobility

The canonical view (Sims and Schaeffer 2014 p 613) is that new light-duty vehicles' tractive load—the power or energy needed to move them—can shrink ~25%, and their fuel use by at least half by 2030 when powertrains are also improved. Yet the underlying analyses overlook important integrative design opportunities to save even more energy and money. Just as shrinking buildings' HVAC equipment can often pay (or more) for the efficiency gains that shrink it, so reducing tractive load by reducing a vehicle's mass, drag, or rolling resistance can shrink its propulsion system (powertrain) for an offsetting saving in capital cost. For example, BMW's 4×-efficiency (1.9 L-equiv/100 km) *i3* electric car pays for the carbon fiber in its passenger cell by needing fewer batteries (Loveday 2011), making that ultralighting free and recharging faster. This tactic is effective in automobiles because about two-thirds of their tractive load is caused by mass (or ~90% in India with slower driving), and because ~79% tank-to-wheels energy losses in today's typical new internal-combustion-engine (ICE) powertrains avoid ~5 units of powertrain loss per unit of avoided tractive load, leveraging ~6 units of saved fuel at the tank (down from 7 in the 1990s). Smaller powertrain is most valuable in electric vehicles, at least until batteries or fuel cells become much cheaper.

2.2.1. Light-duty vehicles

Automotive-industry whole-vehicle designs have confirmed that 2–3× efficiency gains without, or 4–8× with, electric traction can become highly cost-effective if the vehicle is optimized as a system (Cramer and Lovins 2004, Lovins 2015a, 2018b); yet traditional measure-by-measure supply-curve analysis makes potential savings look >2× smaller and costlier, and often adds needless compromises. Tractive load reductions alone, at modest or even negative net cost, have been demonstrated at over twice the canonically assumed 25%, and mass reductions at >70% (*id.*). As with buildings, small savings can cost more than big savings, whose marginal cost at first rises, but can decline again as whole-vehicle synergies emerge at very high savings. This is visible only in whole-vehicle designs (Lovins 2018b)—not in the universally used technology-by-technology supply curves. So while literature acknowledges (Sims *et al* 2014 p 624) that auto efficiency gains of ⩾50% by 2030 are feasible at 'very low, or even negative, societal costs' including saved fuel and externalities, the actual potential is considerably larger and cheaper with integrative design.

No official analysis has yet seriously considered this possibility despite convincing evidence from the industry's own designs (Lovins 2018b). To show why this gap matters, figure 2 compares the US National Research Council's (2002) (aqua) and (2015) (blue) supply curves of potential auto efficiency—dots for light trucks, dashes for cars—and independent 1996–2001 curves (gray and olive) with 14 specific designs:

- in red and purple, two market vehicles surprising in their time—the subcompact 1992 Honda *VX* (Koomey *et al* 1993) and 2004 Toyota *Prius*—showing the *Prius* powertrain's marginal price for 2007 and 2017[11];
- in violet, a major OEM's unpublished 2007 light-metal ICE high-volume production compact car virtual design with 60% higher efficiency and ~$1030 (2000 $) higher marginal price than its steel base model (Lovins 2018b);
- in magenta, a 52-mpg ultralight-steel ICE car designed by Porsche Engineering Services (ULSAB-AVC 2002), and a rough RMI estimate of its 2002 and 2017 cost for a 74-mpg hybrid-electric variant, both illustrating a conventional alternative way to save fuel;
- in brown, simulations of the next two cases' base vehicles (the *Conventional Wisdom* average car and average light truck from Lovins *et al* 2004), consistent with NRC's 2002 assumptions;
- in dark green, Hypercar, Inc.'s and two Tier Ones' 2000 full virtual design (Cramer and Lovins 2004) of the *Revolution* all-wheel-drive carbon-fiber SUV with ICE or hybrid powertrain;

[11] The estimated marginal manufacturing cost of a 2017 *Prius*'s hybrid powertrain, ⩽$2104 (2000 $) (EPA (US Environmental Protection Agency) 2016 pp 2-350 and 2-399; K G Duleep, personal communications, 3–4 August 2018), times the conventional 1.5 multiplier, yields marginal MSRP ~$3052; the minor 2004–17 efficiency shifts are not plotted.

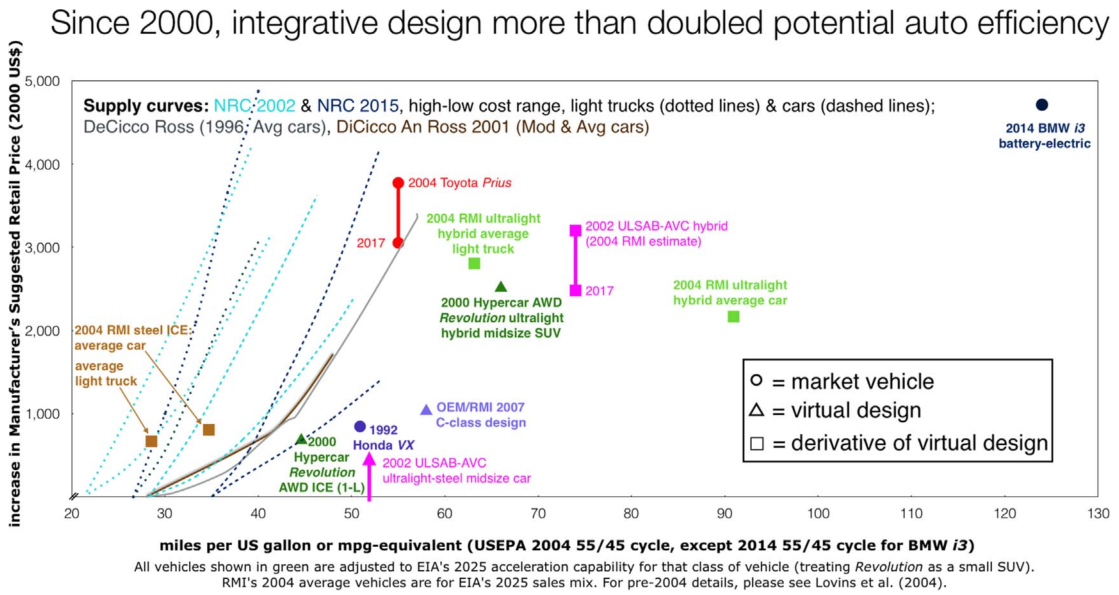

Figure 2. Conventional technology-by-technology incremental supply-curve analysis (aqua and blue curves NRC 2002, 2015, gray curve DeCicco and Ross 1996, olive curve DiCicco *et al* 2001) misses the potential for whole-vehicle integrative design to reveal a 2–3× larger efficiency potential, often at lower cost—the expanded design space beyond ~50 mpg (Lovins 2018b). The 2000 *Revolution* carbon-fiber hybrid crossover SUV design (dark green) whose ICE variant falls on NRC's 2015 low-cost car curve, and the light-green variants inferred from *Revolution*, all cost less than the *Prius* metal hybrid, so advanced composites' fuel- and life-saving advantages are roughly free or better[13]. Combined with the electric powertrain whose shrinkage pays for their carbon fiber, such vehicles (e.g. the *i3* market vehicle in dark blue) can save well over twice the fuel that NRC predicted, at lower cost than incremental supply curves' extrapolation. The illustrated metal ~50–60-mpg non-electric market (purple) and OEM-virtual-design (violet) vehicles similarly cost less than supply curves predict. Thus these four market vehicles, four virtual designs, and four variants illustrate how the standard analytic methodology used in current efficiency regulation grossly underestimates the efficiency and overstates the cost that integrative design can achieve.

- in light green, the simulated equivalent average light-truck and car variants (the latter, at 91 mpg, achieving 2.6× the efficiency of its brown base case at a marginal price only $1361 higher—~2–5× less than implied by extrapolating the aqua curves by NRC, which considered such high efficiency impossible); and
- in dark blue at the upper right, falling on the same curve as such a virtual car design, BMW's 124-mpge 2014 *i3* midvolume production vehicle, whose carbon-fiber passenger cell (Marklines 2015) and battery-electric powertrain are associated with a retail price premium of ~$4721 (2000 $)[12].

This modern *i3* datum demonstrates far higher equivalent efficiency than the 2015 NRC supply curves imply for comparable marginal cost. Clearly the standard (Greene and DeCicco 2000), incremental, technology-by-technology approach omits well over half of the actual design space already demonstrated via integrative design. Moreover, NRC's supply curves (except cars' 2015 low curve) steepened from 2002 to 2015, implying diminishing returns to investment in greater efficiency, yet the *i3* proves that expanding returns from integrative design (Munro and Associates 2015) can be profitably captured in the marketplace.

The ultralighting and whole-vehicle integrative design that yielded two-thirds of the four green points' major fuel savings (Cramer and Lovins 2004, Lovins *et al* 2004) thus opens up a vast new design space—the entire right-hand one-half to two-thirds of the graph, doubling or tripling expected potential fuel savings, yet at lower cost. Thus canonical incremental-supply-curve analysis is obsolete. It makes automotive efficiency look severalfold smaller and costlier than whole-vehicle integrative design can achieve. Therefore climate modelers are greatly underestimating efficiency potential, current auto efficiency standards (now under attack in the US as unachievable) are severalfold more conservative than had been thought, and electrification can be far cheaper, hence faster to scale, than today's high-tractive-load platforms are yet exploiting.

2.2.2. Heavy vehicles

Whole-vehicle design can also cost-effectively triple heavy-truck efficiency (Lovins *et al* 2004, Ogburn

[12] The BMW *i3*'s unique clean-sheet design has no metal-body or non-electric base model, so its marginal price cannot be calculated bottom-up—but can be directly estimated by comparing its retail price with that of a market surrogate for a base vehicle. The steel ICE 27-mpg 2014 MINI Cooper (a BMW marque since 2000) Countryman John Cooper Works or '*JCW*' base model has driver attributes, functionality, utility, amenity, and market positioning very similar to the *i3*'s. (The only material differences are the *JCW*'s 153- rather than 93-mph top speed, 4.6× lower mpge efficiency, and 2.2× larger turning radius.) The graph thus shows *i3*'s 2014 retail price (MSRP) premium of $6275 (2014 $), using the GDP Implicit Price Deflator.

et al 2008, Lovins and Rocky Mountain Institute 2011). IPCC accepts doubled efficiency for long-haul trucks by 2030 at negative cost (Sims and Schaeffer, p 624)—the norm already proven, for conventional tractor-trailer rigs without compound trailers, by truck-makers' road tests under DOE's Supertruck program and reinforced by major demonstrated operational improvements (www.runonless.com). Tripled to quintupled airplane efficiency also looks feasible and worthwhile based on authoritative virtual designs by Boeing, NASA, and MIT—even more with liquid-hydrogen or electric propulsion (Lovins *et al* 2004, Lovins and Rocky Mountain Institute 2011). And savings on the order of half or more have been designed in a variety of ships (*id.*).

2.2.3. Mobility systems

Shared, connected mobility systems enabled by wireless informatics offer further design integration for people (Johnson and Walker 2016) and freight (Agenbroad *et al* 2016). Potential savings expand further with improved urban form (Sims *et al* 2014) and density (Creutzig *et al* 2015, Güneralp *et al* 2017) and by competing various ways to move people or goods against ways not to need to. All these richly complex opportunities, collectively able to provide the same or better mobility or access with severalfold less driving and far less hauling, depend upon or substantially expand with integrative design of vehicle platforms.

2.3. Industry

Upwards of half, perhaps three-fifths, of the world's electricity runs motors, chiefly in industry. The two standard improvements—more-efficient motors and adjustable-speed drives—save ~2× less electricity at ~5× higher unit cost than a whole-drivesystem retrofit, because 28 of its 35 improvements are free byproducts of the first seven (Lovins *et al* 1989, Fickett *et al* 1990). But even bigger improvements are available in the most common systems that motors drive, and should be done first to make their motor systems smaller, hence cheaper.

Half the world's drivepower runs pumps and fans. Making their pipes and ducts fat, short, and straight rather than thin, long, and crooked can save ~80–90+% of their friction (Stasinopoulos *et al* 2009, Chan-Lizardo *et al* 2011 ch 6), and typically pay back in less than a year in retrofits and less than zero in newbuilds (Lovins 2005 pp 16–17, 2015a; P Rumsey PE FASHRAE and E L Lee, personal communications, 2017). Compounding losses—in power plant, wires, inverter, motor, pump, piping—lose ~90% of the power plant's fuel energy. But reversing those compounding losses into compounding *savings*, from downstream to upstream, enables one unit of friction or flow saved in the pipe to leverage ~10 units of saved fuel, cost, and emissions at the power plant. Thus full global optimization of pipe and duct systems could in principle save, with enticing profits, enough pump and fan energy to displace roughly a fifth of the world's electricity or half its coal-fired electricity. Probably no official climate assessment includes this major opportunity.

These drivesystem and fuel-handling opportunities are just the start of industrial integrative design. One practice's systematic whole-system redesigns for more than $40 billion worth of diverse industrial facilities typically found energy savings ~30%–60% in retrofits with paybacks of a few years, or ~40–90+% in newbuilds with nearly always lower capital cost. These savings, severalfold larger and cheaper than comparably skilled practitioners' dis-integrated redesigns, are illustrated by examples like these:

- Texas Instruments' microchip-making 'R-fab' in Richardson, Texas, saved 20% of its energy (without using the two most important recommendations, delayed to later fabrication plants), 35% of water, and 30% of capital cost, or $230 million (TI 2010, McGill 2006)—partly through comprehensive efficiencies that shrank the supporting equipment (providing chilled water, clean air, vacuum, etc) enough to eliminate one of its normal two floors. R-fab's energy saving later reached 40%, and the average TI chip's specific manufacturing energy fell 65% during 2005–17 (Westbrook 2008). A subsequent conceptual design for a competitor's next fab was expected to save two-thirds of energy, half of capital cost, and all 22 000 tons of chillers.
- The 2009 EDS-designed Wynard data center in the North of England (Koulos 2009) used 73% less non-IT electricity and 98% less cooling and pumping energy than a nominal base design, with 3× the computing per kW and normal capital cost—but EDS estimated that realizing its full potential would have saved ~95% of the electricity and ~50% of the capital cost.
- A retrofit design at the world's largest platinum mine (Anglo American, LLP 2004) was expected by its owner to save up to 39% (26% with confidence) of its energy use with a 2–3 year payback while increasing product recovery, safety, labor productivity, and strategic opportunities.
- Retrofit designs for Shell's most efficient oil refinery, a giant LNG liquefaction plant, and a North Sea platform were respectively expected to save 42%, ⩾40%, and ~100% of energy with paybacks of a few years, while a new $5b Fischer-Tröpsch gas-to-

[13] Other key 1990s RMI claims validated by the first midvolume carbon-fiber car, BMW's *i3*, include ~2.5–3.5× mass decompounding (Kranz 2010, confirmed by Greil (2018)) plus simplified manufacturing with ~2/3 less capital, halved assembly time and electricity use, 70% lower water use, and no conventional body shop or paint shop.

liquids plant was expected to save >50% of its energy and ~20% of its capital cost.

- One of the world's largest industrial facilities, Tesla's battery Gigafactory, replaced 1 MW_t of proposed gas boilers with 15 kW_e of heat pumps for solvent redistillation with a ~1.5 K ΔT—a ~98.5% site energy saving. An independently verified European process-heat retrofit similarly saved 92% of natural gas use (Norman Crowley, personal communication, 30 June 2018).

Such anecdotes cannot be widely generalized because industries and processes are so heterogeneous. Some projects, too, were designed but not yet built, often because corporate capital constraints overrode local managers' enthusiasm. Many remain proprietary. Yet practitioners who examine the evidence of published cases are left in no doubt about their calculated or measured performance. It is therefore all the most astonishing that even an opportunity as striking as the big-pipes/small-pumps example is not yet in any official study, industry forecast, IPCC analysis, or (save Stasinopoulos *et al* 2009) engineering textbook, and is not yet in the standard practice of the large firms most noted for outstanding efficiency programs and cultures. Why not? Apparently because it is not a technology; it is a *design* method, a category widely overlooked.

Applying integrative design across sectors reveals common themes. The ~10× downstream-to-upstream amplification of energy saved in pipe/pump systems is analogous to the ~5–7× amplification of reduced tractive load back to fuel savings in autos. Using smaller (or eliminated) HVAC equipment in buildings to pay up front for the efficiency that displaces it is like using smaller powertrain in an auto to help pay for lightweighting, or using smaller pump and motor systems in industry to pay for fatter pipes. Identical methodological errors also occur across engineering disciplines and applications. Optimizing thermal insulation in cold-climate buildings by counting only the present value of the saved fuel but not also the avoided capital cost of the heating system is analogous to optimizing pipe diameter by counting only the present value of the saved pumping energy but not also the avoided capital cost of the pumping equipment. Correcting such pervasive errors needs a return to the clear-eyed Victorian whole-system engineering that made John Ericsson (1876) argue from geometry, 'I strongly recommend engineers who may be called upon to transmit mechanical power by compressed air not to aim at economy by employing tubes of small diameter.'

Even the astonishing savings just illustrated may prove conservative. A leading industrial-efficiency retrofitter, Crowley Carbon, often achieves independently verified site energy savings ~35%–60% (and up to 95% on individual measures), with typical paybacks ~3 y. In 2017, for example, 62 projects in 22 countries saved 37% of primary energy with an average 2.8 y payback. But that firm's practice emphasizes not integrative design but more-conventional hardware improvements importantly reinforced by diagnostic software that continuously specifies and values needed repairs and operational improvements[14]. Such maintenance-driving and savings-sustaining software was not used in another practice's comparable ~30%–60% savings (with similar paybacks) cited above, so adding that software to integrative design should save more energy than either approach alone.

2.4. Summary

The 'efficiency cornucopian' perspective supported by the evidence above often elicits strong skepticism, especially from economic theorists not steeped in engineering practice. But so far, cornucopians seem to offer better foresight than skeptics. For example, when official forecasts assumed little or no efficiency potential, a heretical 1976 reframing of the energy problem around end-use and least-cost suggested that US primary energy intensity could fall 72% in 50 years (Lovins 1976, 2016). Through 2017, it fell 57% in 42 years (figure 3). By 2011, another threefold drop looked feasible by 2050 (Lovins and Rocky Mountain Institute 2011)—twice the savings controversially suggested in the 1970s[15], at a third the real cost—yet now those 2011 findings look conservative. Heresy happens. In due course it quietly becomes conventional wisdom.

2.5. What can the missing efficiency add up to?

We have seen so far that just as traditional analyses emphasize energy supply over efficient use and technological over noneconomic social-science tools and insights, they also emphasize the performance of individual technologies over the design process that optimally chooses, combines, times, and sequences them. This leaves an analytic gap probably as important as the missing hard and soft infrastructures (Creutzig *et al* 2016) that are so important to achieving and maximizing technical efficiency gains.

How much could economy-wide integrative design enlarge energy efficiency's reserves—identified resources economically producible with current techniques? Consider four assessments from 2004 to 2017,

[14] The firm's 2015 internal study of ~130 of its projects over the previous 5 yr found that savings in 70% of cases had decayed by >30%, due mainly to operational changes, facility expansions or use changes, inexpert facilities staff, and management inattention. Such degradation means that the size of the efficiency opportunity is always increasing even if design, technology, and activity levels remain constant (Norman Crowley, personal communication, 30 June 2018).

[15] By 1989, my supply curves of US long-run electric efficiency potential matched the 4× quantity we found in 2000—equivalent to ~3× beyond the savings achieved 1986–2010—based on measured technology cost and performance documented in six RMI/Competitek *Technology Atlas*es (2509 pages, 5135 notes, 1986–92). However, its average real technical cost was 1.6× higher than Lovins and Rocky Mountain Institute (2011) found, so the 1989–2011 improvement in quantity/cost was 2×. This contrasts with the ~6× gain noted in Lovins and Lovins (1991) for 1986–91, due mainly to earlier underappreciation of integrative design.

all broadly consistent with very detailed bottom-up analyses by other independent analysts in the 1980s[16].

The most detailed mid-2000s analysis of how the US could get off oil altogether (Lovins *et al* 2004), Pentagon-cosponsored and widely peer-reviewed, found that a business-led, market-driven transition could double US oil productivity by 2025 at an average cost of $12/bbl (2000 $) with a $70b/y net return, save half of US natural gas use too, and combined with profitable fuel-switching, eliminate US oil imports by 2040 and oil use by 2050, with the same EIA-forecast GDP growth to 2025 and extrapolated to 2050. This 2004 roadmap for relieving US oil dependence did not foresee fracking, yet its demand analysis proved conservative: after 12 years, its controversial projection of US oil consumption exceeded actual use by 1.5 Mb/d, and its projection of net oil imports exceeded actual values by 3 Mb/d without or by 7 with tight oil.

An even deeper peer-reviewed analysis[17] by a 62-member team also incorporated non-oil fuel use and electricity use in buildings and industry to 2050 (Lovins and Rocky Mountain Institute 2011, summarized in Lovins 2015a, 2015b). It detailed how to quadruple US *electric* end-use efficiency at a technical cost averaging $7/MWh (2017 $), implying delivered program-administrator cost $\leqslant$$10/MWh. This finding conservatively applied integrative design in buildings and vehicles, and in industry only for drivesystems and fluid-handling but not processes. It found twice the 2050 electric efficiency gain, at about one-fourth the average technical cost, that the National Academies (2009a) had found feasible for 2030 using older technologies and no integrative design.

Across all sectors, the same analysis (Lovins and Rocky Mountain Institute 2011) combined tripled US primary energy efficiency with quintupled renewable supply to enable a 2050 GDP 2.6× 2010's, yet needing no oil, coal, or nuclear energy and one-third less natural gas. This would reduce 2050 US fossil CO_2 emissions by 82%–86%, cut private internal cost by $5 trillion (2009 $ net present value [NPV] with zero carbon pricing or other externality values), and require no new inventions nor Acts of Congress, but with smart subnational policies in mindful markets, could be led by business for profit. During 2010–17, that study's trajectories for primary and electric energy intensity closely matched their actual declines (not weather-normalized), while renewable deployment was ahead of schedule. Of course, that is only the first 7 yr of the 40 yr transition, yet the savings observed so far are far more consistent with this maverick analysis than with EIA or energy-industry forecasts.

That independent 2011 US study triggered an even more elaborate bottom-up synthesis with a similar level of effort (~32 analyst-years) by the Energy Research Institute of China's National Development and Reform Commission, supported by Lawrence Berkeley National Laboratory, Energy Foundation China, and Rocky Mountain Institute. Published in summary at the 2016 G20 and fully in late 2017 (Lovins *et al* 2016, Zhou *et al* 2016, ERI *et al* 2017, Price *et al* 2017), it showed how to run a 2050 Chinese GDP 7× 2010's by using today's energy 7× more productively; shift supply 67% off fossil fuels (83% in the power sector); burn 80% less coal; cut fossil CO_2 emissions 42% below 2010's; raise GDP per unit of fossil carbon 13×; and save $3.1 trillion (2010 $ NPV with zero externalities). This official study by China's top energy analytic group strongly influenced the 13th Five Year Plan (whose senior energy authors were its advisors), hence Chinese energy strategy and implementation. It appears on track or ahead of schedule so far, though most of it is yet to unfold. India's emerging mobility transformation (NITI Aayog and RMI 2017) exhibits similar promise and dynamism.

Conventional literature can neither reconcile its findings with those of such studies nor refute them, so it typically ignores them. But that is not for their lack of detail and rigor, peer review, or strong and well-documented evidence—only of fit to traditional consensus.

The sectoral evidence in section 2 above implies that integrative design at least doubles the conventionally analyzed savings profitably available in buildings, cars (even without the transformative mobility/IT mashup), heavy trucks including their logistics, airplanes, industrial drivesystems (which dominate industrial electricity use), their downstream fluid-handling systems (whose opportunity is even larger), and significant industrial processes. This seems broadly consistent with the four comparisons above—three for the US, one for China. Together, this combination of technology-specific and economy-wide evidence, often showing savings >2× those conventionally described, supports this paper's claim that integrative design could, if widely adopted and well practiced, increase the world's energy productivity reserves by severalfold, generally at lower cost than traditionally assessed.

The complex and opaque econometric models of the mid-1970s underpredicted[18] 2000 US energy efficiency by up to 2×—just as their far more sophisticated successors, with similar methodologies and mindsets, lately underpredicted (by even more)

[16] These found a potential (all converted to 1986 $) to save half of total Swedish electricity at an average cost of 1.3¢/kWh (Bodlund *et al* 1989), half the electricity in Danish buildings at 0.6¢/kWh or three-fourths at 1.3¢/kWh (Nørgård 1989), and 80% (including fuel-switching) in West German households with a 2.6 year payback (Feist 1987). Most potential savings not yet captured have expanded since then.

[17] Like the previous analysis, it incorporated demand rebound to the extent justified by credible literature.

[18] In contrast, Lovins (1976)—independently found (Craig *et al* 2002) to offer uniquely accurate foresight about 2000 US energy demand—relied on no computer models. Using only a sliderule and an HP-35 calculator, it constructed an 'impressionistic' scenario 'driven by a large number of engineering and economic calculations…' (*id.*). Its semiquantitative, scenario-like, transdisciplinary approach also permitted valuable foresight into the electricity sector (Burr and Lovins 2014, Lovins 2013, 2016, Flin 2016).

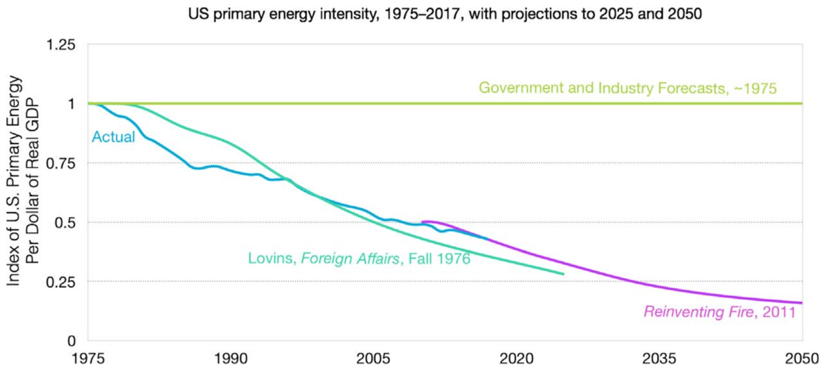

Figure 3. US primary energy intensity has more than halved as controversially foreseen in 1976, but another threefold drop is now in view and keeps getting bigger and cheaper. Data from Lovins (1976), Lovins and Rocky Mountain Institute (2011), and ('actual') US Energy Information Administration *Monthly Energy Reviews*.

renewables' plummeting cost and soaring adoption. Models based on scarcity and depletion cannot generate or tolerate expanding returns—e.g. when we buy more photovoltaics (PV) and windpower, they get cheaper, so we buy more, so they get cheaper. IEA's wind and PV forecasts respectively rose 5× and 23× since 2002 without catching up with reality. Today's global PV capacity is 40× IEA's 2002 forecast: fundamental physical and commercial phenomena have made PV costs drop steeply for decades, not rising in a single year, so in 2017, PVs added more global net capacity than did all fossil-fueled generators, and modern renewables were 64%[19] of net global capacity additions (FS-UNEP-BNEF 2018). Modern energy efficiency too can get bigger but cheaper by combining mass-produced devices, revolutionary IT and network progress, *and* the technical and economic synergies of integrative design, spreading at the speed of valuable ideas—subject to all their obstacles, but with a seemingly growing potential to change how design is taught, done, and valued. Thus the growing realization (Creutzig *et al* 2018) that 'Research on climate-change mitigation tends to focus on supply-side technology solutions. A better understanding of demand side solutions is missing' should add *design*, and specifically integrative design, to its worthy catalog of tools and disciplines that analysts should integrate and IPPC's forthcoming Sixth Assessment Report should consider (Mundaca, Ürge-Vorsatz and Wilson 2018).

3. Implications for climate protection

The rigorous US and Chinese studies summarized in section 2.5 permit a speculative, simplistic, but instructive thought-experiment. Adopting also a comparable synthesis for Europe (European Climate Foundation 2010) and using the US as a surrogate for non-EU OECD and China for non-OECD, both prorated on GDP growth to 2050, suggests that a 2 °C climate trajectory could deliver the same or better energy services roughly \$18 trillion cheaper (2010 \$ NPV) than business-as-usual. Emerging assessments and some newer options suggest that reinvesting part of that surplus in natural-systems carbon removal (Clarke *et al* 2014, Edenhofer *et al* 2014, Paustian *et al* 2016, United States Government 2016, Griscom *et al* 2017, Abramczyk *et al* 2017, Pratt and Moran 2010, Stanley *et al* 2018) could probably achieve a ~1.5 °C trajectory, still with trillions of dollars left over, thus easing climate politics. This integrative, bottom-up, engineering-based potential merits intensive exploration.

An important step in that direction occurred in June 2018 when Grübler *et al* (2018), working within the standard integrated assessment model framework, published a 1.5 °C scenario with far higher global energy efficiency than previously assumed by the IAM community. This Low Energy Demand scenario enables 80%-renewable 2050 supply and more-granular, faster-deployable scale, needs severalfold lower supply-side investment and far less policy dependence, leaves an ample 50% 'safety margin' in demand, yields major positive externalities, and needs no negative emissions technologies. Yet these impressive outcomes seem not to apply integrative design (as described here) except in passive buildings. Many assumed technical efficiencies—as in vehicles, structural materials, and crosscutting industrial technologies—seem substantially lower than those documented here (e.g. assuming new 2050 cars ~58% more fuel-intensive than the mass-produced 2015 model I drive, which in turn could be profitably improved). Grübler *et al*'s 290-EJ 2050 global primary energy demand is less than even the 429 EJ yr^{-1} of the thought-experiment described in the previous paragraph, but is achieved largely by means other than its advanced energy efficiency techniques. Thus Grübler

[19] The FS authors have acknowledged that their 61% figure relied on a Feb 2017 BNEF forecast that nuclear power would add 11 net GW in 2017, but the actual addition (IAEA PRIS) was 0.3 GW, or 0.9 including US upratings.

et al's pioneering low-energy-demand synthesis, though likely to be attacked as unrealistic (much as mine in figure 3 was), is technically quite conservative. Systematically and comprehensively applying integrative design to such low-demand scenarios could make them even more convincing, robust, and attractive, and illuminate the astonishing breadth of the design space for profitable climate-change mitigation. Conversely, Grübler *et al*'s lower energy demand than our thought-experiment illustrates the additional power of non-technological, social-science-based improvements that the latter analysis did not fully reflect.

4. Implications for analytic methodology

Many climate analysts mistake the rear-view mirror for a windshield due to major epistemological differences between economic and engineering perspectives (Lovins 2005). Economic theory cannot reveal whether efficiency's 'low-hanging fruit'—a misnomer for eye-level fruit—will dwindle or grow back faster than it is harvested[20], but experience so far strongly suggests the latter. For example, after decades' effort, the real costs of Pacific Northwest electric savings have nearly halved while their quantity tripled since the 1990s (Northwest Power Planning Council 2016). Real program-administrator costs per saved kWh for 5400 program-years' work (by 36 states' efficiency programs for utilities serving half of US load) stayed 'relatively flat or declining' during 2009–13 (Hoffman *et al* 2017[21]). Thus even without integrative design, learning and scaling effects are still dropping efficiency's costs at least enough to offset any upward-sloping supply-curve[22].

Theorists and modelers still continue to assume that upward slope even as empirical evidence of its reality remains elusive—experience that seldom influences modeled future savings. NYSERDA, for example, found that New York State's achievable electric efficiency potential in 2003 was virtually identical to 1989's, so 'experience has shown that over decades technology advancement is likely to more than keep pace with improving baseline efficiency'; yet NYSERDA (2015), presumably to comfort economic theorists and avoid accusations of overoptimism, assumed learning curves for only a few selected technologies like LEDs. To be sure, there are real and substantial barriers to adopting energy efficiency (e.g. Lovins 1992), and the US has so far saved electricity only half as fast as it has saved directly used fuels, but that gap will probably narrow or vanish (Lovins 2017).

Of course, past performance is no guarantee of future results. Yet Dow Chemical Company, having saved >\$9 billion in 1994–2010 on <\$1 billion of energy efficiency investments, continues to save ever more—\$27 billion to 2015 (Almaguer 2015). That progress builds on its Louisiana Division's 1981–93 legacy of increasing both savings and their financial returns, averaging >200% in nearly 900 projects, as shop-floor engineers, for a dozen years, kept finding new opportunities faster than they used up the old ones (Nelson 1993)[23]. The supply curve of the efficiency resource dropped down by more than it sloped up, even in an extremely cost-conscious and technically skilled industry that's intently focused on energy because energy is half its total cost. So should not other energy users and uses also offer important opportunities for learning, scaling, and innovating to outpace efficiency's 'depletion'—especially when one learns that Dow achieved those impressive energy savings *without* yet applying integrative design as described here?

Today's efficiency-and-renewables revolution is not only a convergence of technology plus design plus information technology. It reflects no less than the emergence of a new economic model. Today's energy transition exhibits not the Ricardian economics of scarcity, like diminishing returns to farmland and minerals, but the complementary modern economics of abundance, with expanding returns (Arthur 1999, 2004, Gritsevskyi and Nakicenovic 2000, Nagy *et al* 2013). These flow from mass manufacturing of fast granular technologies with rapid learning, network effects, and mutually reinforcing innovations. With those new driving forces, today's emergent paradigm for profitable climate stabilization envisions an energy-and-land-use transformation not slowed by incumbents' inertias but sped by insurgents' ambitions (Rockström *et al* 2017, Abramczyk *et al* 2017),

20 The same seems true for US water productivity, which during 1950–2010 rose 3.31×, 43% more than primary energy productivity's 2.31×. Few people noticed either of these revolutions. The increasingly urgent energy/water nexus will put more pressure on both.

21 Hoffman *et al*'s (2018) two-years-longer dataset, helpfully clarified by the authors (personal communication, 20 July 2018), suggests otherwise for the biggest and often most mature third of US electricity-saving programs, but national aggregation, data-quality issues, diverse and shifting evaluation details, and modest statistical fidelity do not yet make the trend they identify a convincing demonstration of 'depletion' effects, so it should be interpreted with caution. Long-term trends in a single utility's or region's portfolio, as in the Pacific Northwest example above, are more persuasive if evaluation methods and assumptions are relatively stable, but unfortunately such datasets are rare. Until more are identified that contradict the limited but clear evidence of stable or falling real cost, the conventional assumption that efficiency's real cost will rise as more is bought seems unjustified and improper.

22 Efficiency does not necessarily cost more even at the level of simple and important *components*. For some, supply curves of efficiency seem to slope downwards (Lovins 1996 n 14), and for others, they're flat: e.g. the 2010 North American trade price for the most common kind of industrial motor is uncorrelated with efficiency up to ⩾100 hp, and only loosely correlated at 400 hp (McCoy 2011). Yet it is hard to find any economic literature that acknowledges or explains such surprisingly basic empirical anomalies.

23 The main obstacle to discovering and then persisting in such successive and continuously improving tranches of savings was the theoretical belief that they could not exist.

and converging, as Jon Creyts remarks, to the speed and cost not of infrastructure but of software.

5. Conclusions

The energy efficiency generally understood and pursued today is the costlier minority of the efficiency resource. We need to identify and exploit the rest too. With energy efficiency as its cornerstone and needing its pace redoubled, climate protection depends critically on seeing and deploying the entire efficiency resource. This means extending modern net-zero or net-positive and deep-retrofit building design philosophies—examples of integrative design—into industry, vehicles, mobility, and their links to IT and urban form; broadening our climate-change-mitigation analytic framework from components or devices to whole systems; and replacing theoretical assumptions about efficiency's diminishing returns with practitioners' empirical evidence of expanding returns.

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