Profitably Decarbonizing Heavy Transport and Industrial Heat

Transforming These "Harder-to-Abate" Sectors Is Not Uniquely Hard and Can Be Lucrative

Emeritus Insight Series / July 2021

RMI

Emeritus Insight Series

RMI publishes periodic thought leadership from our founders and former colleagues. This report was independently authored by RMI's cofounder and chairman emeritus, Amory B. Lovins.

Suggested Citation

Amory B. Lovins, *Profitably Decarbonizing Heavy Transport and Industrial Heat: Transforming These "Harder-to-Abate" Sectors Is Not Uniquely Hard and Can Be Lucrative*, 2021, **https://www.rmi.org/profitable-decarb/**

Acknowledgments

The author appreciates insightful review comments by Josh Agenbroad, Vahit Atakan, Charlie Bloch, Phillippe Block, Sandra Bolvin, Kingsmill Bond, Dennis Bushnell, Tom Dinwoodie, Janet Ginsburg, Joseph Goodman, Cameron Hepburn, Laura Hutchinson, Tomas Kåberger, Tom Keough, Lucy Kessler, Thomas Koch-Blank, Jonathan Koomey, Ryan Laemel, Tankred Lenz, Christoph Levy, Mike Mason, Dave Mullaney, James Newcomb, Juan-Pablo Osman-Letelier, Mike Roeth, Mike Schlaich, Maria van der Hoeven, and Harald Winkler. Any remaining errors or omissions are the author's sole responsibility.

We thank Fred and Alice Stanback for supporting the production of this report.

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Introduction

To avoid the worst risks of runaway climate change, the world must cut global greenhouse gas emissions—chiefly carbon dioxide from burning fossil fuels—in half by 2030 and to about zero by 2050. Of that CO_2, around 35% comes from heavy transport[1] (in declining order, big trucks, ships, airplanes, trains, and buses) and from industrial heat to make energy-intensive materials.[2] Both sectors are supposedly "hard-to-abate," so most climate models emphasize costly and unproven ways to extract CO_2 from smokestack emissions or even from thin air.[3] Those gloomy assumptions drive fatalistic apathy, fitful policy focus, and fervid opposition—but are unsound.[4]

Emissions from heavy transport and industrial heat may actually be no harder to abate than the comparable total from buildings (19%) plus light transport (12%)—just differently hard. Vast and fast abatements are never easy. Yet a fresh look reveals many novel and timely opportunities.

Rather than rising 50% by mid-century, CO_2 emissions from heavy transport and industrial heat could fall to about zero or less, as eminent business leaders convincingly found in 2018.[5] They estimated modest costs: about 0.24%–0.45% of 2050 global GDP using only supply-side changes, or 0.15%–0.25% adding more-productive use of transport and materials. These lower values reflect lower renewable energy costs, available then in some places and now in many more, as explained in the next section.

Of note, that assessment found that 20% of CO_2 could be saved in heavy transport by modal shifts and smart logistics and 35%–40% by technical efficiency gains. In heavy industry, 40% of CO_2 could be saved by more fully reusing steel, aluminum, and plastics. But today's even bigger and rapidly growing menu might turn those modest costs into significant profits, triggering trillions of dollars in creative destruction.

A rich stew of new technologies, materials, design methods, financial techniques, business models, smart policies, and aggressive investments could in this decade revitalize, relocate, or displace some of the world's most powerful industries. A companion paper surveys those shifts' opportunities for business strategy.[6] Here we complement such implementation accelerators by explaining and documenting the more technical contours of how, by the 2030s, trucking, aviation, and shipping could be decoupling from climate. Steel, aluminum, cement, and plastics too could take new forms, saved and made in new ways and unexpected places under novel business models. All these emergent transformations build on today's revolution in clean electricity.

Electricity's Race to Carbon-Free and Almost-Free

Even as the pandemic shrank energy demand and fossil fuel supplies, lower costs and risks propelled faster growth in carbon-free renewable sources, chiefly wind and solar power. These modern renewables now provide the cheapest unsubsidized bulk power for 90% of world demand—soon for virtually all demand.[7] By the time total energy demand recovers, renewables may well have grown enough to provide all its increase, tipping fossil fuels into permanent decline.[8]

World coal use peaked in 2013. World auto sales peaked in 2017 at an annual growth rate less than the annual sales of electric vehicles since then; in 2020, plug-in auto sales rose 43% while total auto sales fell 14%.[9,10] Oil and total fossil-fuel use probably peaked in 2019.[11] Capital fled. By mid-2020, the world's top 16 listed hydrocarbon companies combined were worth less than Apple.

Fossil-fueled electricity peaked in 2018; Bloomberg New Energy Finance expects the power sector's CO_2 emissions never to recover to their 2018 peak.[12] Renewables added 90% of the world's new electric generating capacity in 2020, are expected to average 95% through 2025,[13] and produced approximately 29%–31% of the world's electricity in 2020,[14] overtaking fossil-fueled generation in Europe and both coal and nuclear generation in the United States.[15] The cheapest unsubsidized 2019 wind and solar sold for a stunningly low $17/MWh,[16] heading below $10 in this decade.[17] Indeed, April 2021 brought a reportedly unsubsidized winning Saudi solar power bid of $10.4/MWh, a decade sooner than most analysts expected.[18, 19]

In 2020, with unsubsidized prices in six nations falling to $26–$30 for onshore wind and $23–$29 for solar,[20] the world added a record 278 net gigawatts (GW) of renewables.[21] This is nearly 50% more than the previous year, despite the pandemic—and brought total installed wind-plus-solar capacity to approximately

1,450 GW. In May 2020, the International Energy Agency (IEA) expected 50% growth in renewable output during 2020–25, to nearly 10 million GWh, "equivalent to the combined demand of China and the European Union," encouraged by many countries' net-zero emissions targets.[22] A year later, IEA raised that forecast by nearly two-fifths—yet still, it seems, without modeling solar and wind power in a way that fully captures the increasing returns causing their rapid growth.[23]

Coal, gas, and nuclear stations therefore struggle, with no business case to build and little or none even to run.[24,25] The less they run—grids generally use most the generators with lowest operating cost—the less their dwindling revenues can cover construction debt, pushing them out of the market and thereby stressing their jilted fuel suppliers and the whole fossil-fuel value chain. (Many widely used analyses ignore this disruptive competition, treating long-run capacity factor as a constant rather than an evolving variable. This understates the actual costs of fueled plants and inflates a bubble in their asset value.[26])

New unsubsidized renewables with battery storage cost less to build and run than just running 39% of the world's coal plants in 2020 and an expected 73% by 2025.[27] Thus immediately replacing every coal-fired power station worldwide, using efficiently structured finance, would be cost-neutral by 2022 and save over $100 billion/y by 2025, plus provide climate and health benefits.[28] Stranded gas-fired plants and their fuel infrastructure come next. As Bloomberg New Energy Finance (BNEF) concluded in December 2020,[29] "Variable renewables and back-up are the cheapest new-build option to meet a flat load"—not the venerable "baseload" units of a bygone era—and that backup often needs no fossil or nuclear fuels either.[30]

This market-driven shift to renewable electricity unleashes powerful deflationary forces across the economy,[31] and will transform geopolitics.[32] The parallel revolution in electric vehicles, with GM pledging to exit fueled autos by 2035, Volvo and Ford Europe by 2030, VW reportedly by 2026, and Jaguar by 2025, makes renewable deployment faster and cheaper. Their batteries—in smart bidirectional-

charging autos,[33] retired from them, or simply made cheap and ubiquitous by their volume—meanwhile make rooftop 24/7 solar power cheaper than grid power (and more resilient: most outages start in the grid).

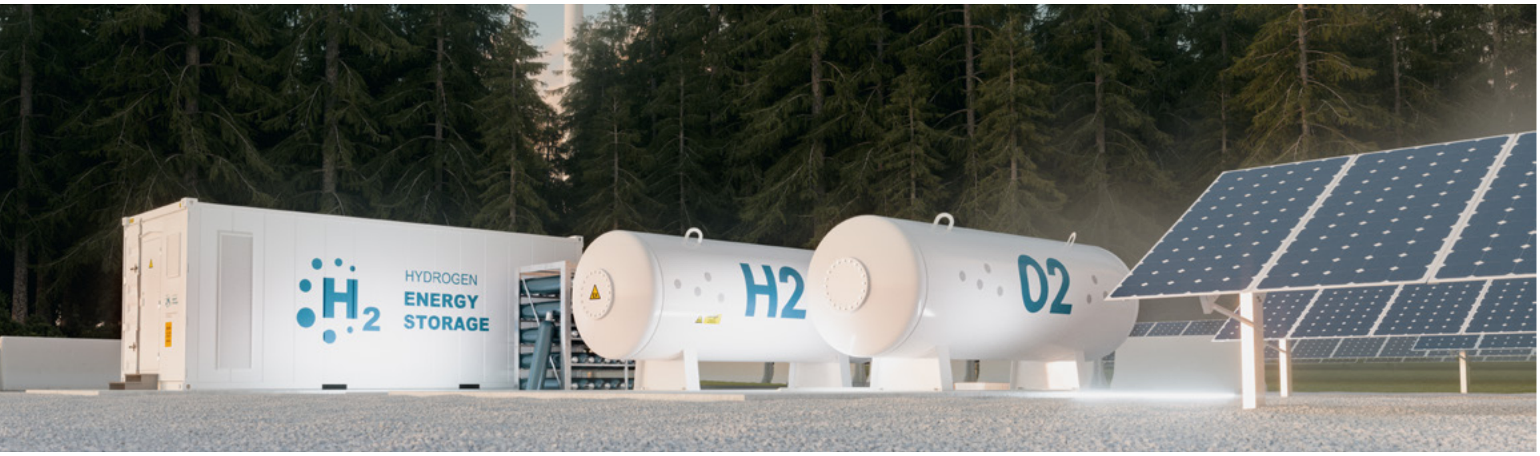
Most new California renewable projects already incorporate batteries, helping US storage additions just in 4Q2020 to exceed the 2013–19 total.[34] The world in 2020 added about as much lithium-ion grid storage capacity (5.3 GW, 10.7 GWh[35]) as nuclear power (5.52 GW, nearly all offset by nuclear retirements). Eight other kinds of carbon-free grid-flexibility resources cost even less than batteries.[36,37]

Perhaps because traditional economics teaches us to allocate scarcity, not spawn abundance, an important dynamic is often overlooked. It takes over as those grid-balancing resources augment renewable portfolios over the next decade or two, all getting ever cheaper, hence more dominant, hence even cheaper. Capacity to ensure reliable service in the calmest and cloudiest weather is often several times what the best conditions require. Such generous capacity still wins even at present prices—which will halve again with volume—and can be further expanded with modest investments.

Experts unused to such "overcapacity" debate how much extra solar, wind, and grid-balancing capacity we'll need to supply electricity reliably in those worst conditions. But they ask only whether we can afford enough renewables—not what they'd be worth if bought. Once they're bought for reliability, most of the time the renewable system can produce severalfold more electricity than buildings, present industry, and electric automobiles need. Those frequent surpluses[38] —their capital costs paid, their operating costs near zero—can be profitably priced to displace the fossil fuels burned directly in heavy transport and industry. Crediting that surplus flips the story: it reveals how to win the decarbonization endgame by displacing and undercutting fossil fuels in heavy vehicles and industry too, while creating a fat extra margin for renewable owners.[39] Fossil-fuel game over.

Thus cheap, ubiquitous, renewable electricity will enable and reward promptly electrifying virtually all fossil-fuel uses, either directly or by making renewable electricity into carbon-free hydrogen or ammonia,[40] and most easily if electricity is very efficiently used. In 2020, global solar and wind power produced about a tenth of global electricity. Global electricity in turn was three times smaller than fossil fuels burned directly for heat and mobility, leaving plenty of renewable growth to elicit and reward.[41]

That electrification often brings first-mover advantage, creating lock-in for the nearly all-electric future ("nearly" because some direct solar heat and solar fuels may still compete). But as we'll see, and as the companion paper elaborates, this logic applies to clean-energy buyers as well as sellers, so lock-ins on both the demand and supply sides can reinforce each other to create a unique double lock-in. Here's how that game-changing strategy for the carbon-free endgame could play out,[42] starting with the heavy transport that emits more than two-fifths of "harder-to-abate" CO_2.



Heavy Transport

Trucks

Of the transport that uses roughly half the world's oil, three-fourths fuels road vehicles, among which trucks rank second, using about 18% of all oil compared with 27% for passenger vehicles. More than half of heavy transport CO_2, or 7.5% of global CO_2, comes from heavy road vehicles, chiefly 18-wheel Class 8 trucks averaging approximately 6 miles per US gallon of diesel fuel. Better driving can yield 7.25 mpg,[43] and with streamlining and better tires, 10.1 mpg.[44] Major makers' 2016 test trucks got 12–13 mpg;[45,46] one projects about 15 mpg in 2021.[47] Tesla's battery-electric Semi (Exhibit 1) gets over 17 mpg-equivalent (mpge), or probably around 21 mpge with two trailers per tractor,[48] and emits nothing.[49] What does this tripled efficiency imply, and how can it be sped?

Designing out deadweight, air drag, and tire rolling resistance shrinks propulsion needs and may soon recoup electric drive's extra capital cost, just as BMW's 4X-efficiency i3 electric car paid for its carbon-fiber body by needing fewer batteries and simpler manufacturing.[50,51] Efficient trucks also shrink their costly charging infrastructure and power supplies. Coordinating truck arrivals like airplane landings to slot into available recharging bays could minimize waiting, smooth electric loads, minimize electricity prices, and enable valuable grid transactions that earn money while the driver sleeps.

US electric trucks are forecast to grow from 2,000-odd in 2019 to over 54,000 by 2025,[52] sped by major early fleet adoptions, strengthening business cases, and barrier-busting.[53] Europe's largest truck makers have sped by a decade, to 2040, their last sales of CO_2-emitting vehicles.[54]

Exhibit 1 Tesla's 2021 Semi Class 8 Battery-Electric Truck


Image courtesy of Tesla Inc.

Tesla's 2021 Semi Class 8 battery-electric truck promises 500-mile full-load range (the average US haul length)—ultimately about 620 miles with the firm's latest batteries in 2021 production scaleup—plus 400 miles of added range from a half-hour's recharge at 10X Supercharger speed. The 50% base-price premium is said to pay back in two years from halved operating cost (and then a million-mile warranty), and could vanish in this decade with cheaper batteries, since the rest of the powertrain is cheaper than diesel and the rest of the rig should cost little extra.[55] The Semi has 40% sleeker aerodynamics, 3X–5X faster acceleration, and one-third-faster hill-climbing (5% grade, fully laden) than a standard diesel truck. Payload should be within 1 ton of normal as battery weight and about 400 kg of electric motor system are offset by lightening elsewhere,[56] including roughly 3 tons of avoided diesel propulsion system and fuel.

Electric trucking is easiest with single-shift fixed-base vehicles and on longer regular routes. Though often "targeted straight at the taillights" of Tesla,[57] which sold 23% of the world's 2020 battery-electric cars, its many competitors aren't just scaling electric trucks, pickups, and vans; they're filling niches from mining trucks to excavators, garbage and bucket trucks to urban delivery vehicles.[58,59] A thousand vans, rickshaws, and scooters are electrifying 36 Delhi firms' last-mile deliveries as India moves to electrify taxi aggregators like Uber and Ola.[60,61]

Data from 50,000 Shenzhen electric logistics vehicles confirm that rapid electrification of urban logistics is practical and profitable.[62] China's 2019 two-wheeler sales were 61% electric; the government plans to electrify 20% of new cars by 2025 and implied all would be electric by 2035.[63] In big and small vehicles, using batteries and fuel cells,[64] electrification will challenge both oil and advanced biofuels.[65]

Efficient, electric trucks are just the start of efficient trucking.[66] Especially in countries like China and India, eliminating overloading and its road damage would aid efficiency, public health, safety, climate, and profits. Smart logistics and packing can better fill cubic and weight capacity,[67] employ idle trucks, and match trips with loads to minimize backhauls (empty running)—a waste estimated at ~40%,[68] twice the US average, but best practice in the best-suited segments is ~5–8%.[69] Shifting more freight from trucks onto trains, barges, and ships could save ~16% of US trucking to 2050, and probably more abroad.[70] Logistical and modal shifts could cut up to 20% of global heavy transport's CO_2[71]—or more as dwindling bulk-commodity shipments liberate rail and barge capacity.

These technical, operational, and logistical savings all look profitable and can be quick:[72] they halved Walmart's 6,500-tractor heavy-truck fleet's fuel intensity in 2005–15, raising savings to $1 billion/y, then saved another 11% through 2019.[73] Shipped goods too can get lighter, smaller, and made nearby; smarter urban design and transit systems can unclog highways; convoys of autonomous trucks may save energy and scarce drivers; and Pony Express-like relays (so drivers can sleep at home each night) could help relieve that scarcity while better matching vehicles to topographies and nearly eliminating recharging delays.

Policy will help, as a quarter-century of pollution reductions from US trucks prove. The EU requires 30% heavy-truck CO_2-intensity cuts for 2019–30, encouraged by 18 firms with €325 billion/y revenue. California and 14 state-level partners, building on their Zero-Emissions Vehicle automotive rules and tradeable credits, mandated 2024–50 scaleup to 100% zero-emissions trucks and buses—also an environmental justice win, since diesel trucks disproportionately pollute communities of color.

Public bulk procurements can build volume, cut cost, and gain experience faster. "Feebates"—fees on inefficient trucks and rebates to efficient new trucks—can apply social discount rates to private purchases, focusing buyers on lifecycle savings (revenue- and size-neutrally if desired).[74] "Golden carrot" purchase commitments from major-customer consortia could speed and scale radical truck efficiency by derisking makers' development investments.[75,76] This could unbundle buying innovation from buying vehicles, reward bold innovation over timid incrementalism, and transform vendors' and customers' cultures.

All major makers are developing e-trucks—Calstart expects 169 diverse models on the California market in 2021—and the industry is no longer innovation-averse. Battery costs are already falling at least as quickly as solar costs; adding truck batteries to car and utility batteries will drive volume up and price down sooner. Scaling their materials doesn't look seriously problematic.[77] Truckstop-scale recharging is a worthily tough but solvable challenge.

Buses and Trains

Buses use roughly 3% of the world's oil. As with trucks, intercity buses' air drag (halved by Québec's Volvo Prevost) and tire losses are the main energy wasters. The Global Fuel Economy Initiative for global transit buses targets 65% less CO_2/mile by 2035, 95% by 2050.[78] A Class 8 electric truck can go over 500 miles, so an electric bus half its weight can too. Shenzhen built a nearly 4X-efficiency electric bus fleet the size of London's entire bus fleet in eight years. China, where 59% of 2019 new buses were electric, has 99% of the world's half-million electric buses, planned to double by 2025. They drove about 40% of the world's bus-miles in 2020.

E-bus production is springing up from Changsha to Chennai, Burlingame to Kampala. Battery leasing and electric tariff arbitrage look attractive.[79] Most trains, many urban buses, and even some heavy trucks can also use overhead catenaries rather than batteries.

Steel wheels make trains efficient, but reducing weight and air resistance can about redouble efficiency while diesel trains electrify or switch to hydrogen.[80] New transit options, from bus rapid transit to ultralight rail,[81] can slash costs while improving speed and versatility. High-speed rail is becoming an important competitor to less-efficient air travel, and on routes where trains are faster, some European countries are taxing or prohibiting commercial flights.

Airplanes

Aviation emits 3% of global CO_2 but has a total climate forcing apparently ~3X larger (due chiefly to contrail cirrus).[82] At most 1% of the world's people cause most aviation emissions.[83] Flying grew quickly until the 2020 pandemic. Forecast post-pandemic growth, less increased virtual travel,[84] conventionally swamps routine efficiency gains (IATA expects ~30%–45% by 2050), small modal shifts, and replacing kerosene with severalfold-costlier biofuels. Yet aviation "is on the brink of the biggest revolution since the 1930s"[85]—electrification. The National Academies in 2016 said doubling batteries' energy density would take 20 years; it took three. Electric propulsion (at least at cruise) already makes sense for short-haul planes—perhaps mid-hauls if even better batteries succeed, such as safe lithium-air or lithium-sulfur. Long-hauls could use liquid-green-hydrogen "cryoplanes."[86] That's good for climate, bad for oil: BP in 2019 forecast 79% of 2017–40 global growth in refined-product demand would come from aviation.[87,88]

Better engines, lighter, sleeker airframes, and filled seats cut 1960–2000-certified airplanes' block fuel use by 70%. Incremental 2%/y efficiency gains continued so predictably that Boeing's 2025 offering revealed in 2019 (NMA/"797") reportedly matched RMI's 2002 forecast.[89] Yet far better, truly superefficient planes can now offset costlier biofuels and speed electrification.

Little-noticed by most analysts, the best kerosene-fueled jetliners designed a decade ago are three to five times more efficient than today's fleet.[90] Two recent variants (Exhibit 2a and 2b) could save respectively 60% and 72% of fuel compared with 2005 best-in-class models.[91] Such savings look attractive because fuel is a dominant cost, it needs more fuel to carry itself, and lightening a typical US jetliner by one pound saves fuel worth ~$1,000 present value. But even better designs are emerging.

An astonishing 2020 prototype piston-engine business plane with advanced aerodynamics and lightweighting (Exhibit 2c) is reportedly eight times more efficient (18–25 mpg versus 2–3 mpg) and costs six times less to operate than a business jet. Targeting first deliveries in 2025 and perfectly suiting convenient point-to-point route architectures, it could compete with airlines' cost per seat-mile while offering business-jet amenity and convenience, and be a strong candidate for disruptive electrification. A nearly doubled-volume version capable of well over 20 roomy seats has already been designed.

Among other emerging gamechangers, GE Additive's 2017 3D-printed business-jet turbofan engine delivered 10% more power from 5% less weight with 20% less fuel and 99% fewer parts. Simpler manufacturing made a 95%-carbon-fiber mid-1990s Lockheed-Martin Skunk Works fighter-plane design one-third lighter but two-thirds cheaper than its 72%-metal predecessor.[92] Lattices robotically assembled from centimeter-scale plastic cells can form tough 98%–99%-lighter structures (Exhibit 3)[93] with real-time shapes that can morph, displacing mechanical flaps and even passively self-optimizing like birds' wings. To supercharge these innovations, a "golden carrot" customer-consortium commitment to bulk-buy severalfold-more-efficient planes could remove market risk, excite visionary aviation technologists and leaders, and transform aviation forever.

Exhibit 2 Innovative Airplane Designs

Image credits: a: courtesy of NASA, b: courtesy of NASA, c: courtesy of Otto Aviation

Innovative designs like a–b from NASA/Boeing (and others) offer ~60–80% fuel savings using decade-old technologies.[94] Otto Aviation's August 2020 Celera 500L prototype (c), an 8X-more-efficient six-seat luxury plane, could connect almost any US city pair nonstop at 450 mph.[95]

Exhibit 3 Innovative Aviation Technologies

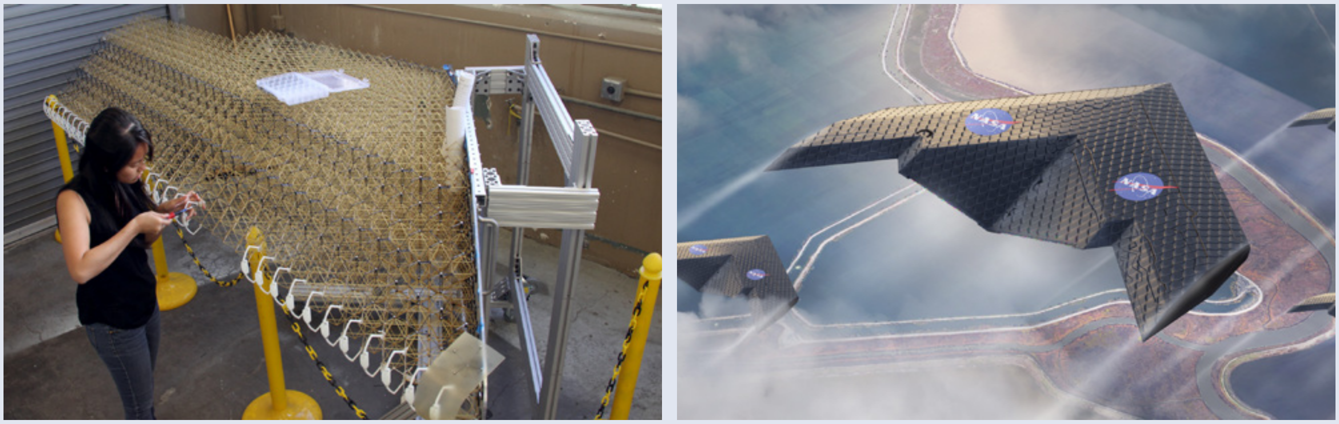


Image credits: left: courtesy of NASA Ames Research Center,[96] right: Courtesy of Eli Gershenfeld, NASA Ames Research Center

An experimental 4.3-m-long wing model made of a membrane-covered lattice of molded plastic cells (L) was 59X or 98.3% less dense than a typical metal airplane wing. With the strength and toughness of bulk elastomers but the gossamer density of aerogel, such structures could make airplanes of any form (R), and continuously self-optimize aerodynamic shape. Lattices made of carbon fiber or commercial carbon nanotubes could be on the order of 10X–100X stiffer and stronger still. Such cellular lattices open revolutionary prospects for ultralighting, aerodynamics, and cost reduction. Already prototyped for cars with Toyota and planes with Airbus, they could even permit a "vacuum balloon," buoyant in but not crushed by the atmosphere, with two dozen times the lifting power of a 747 jetliner.

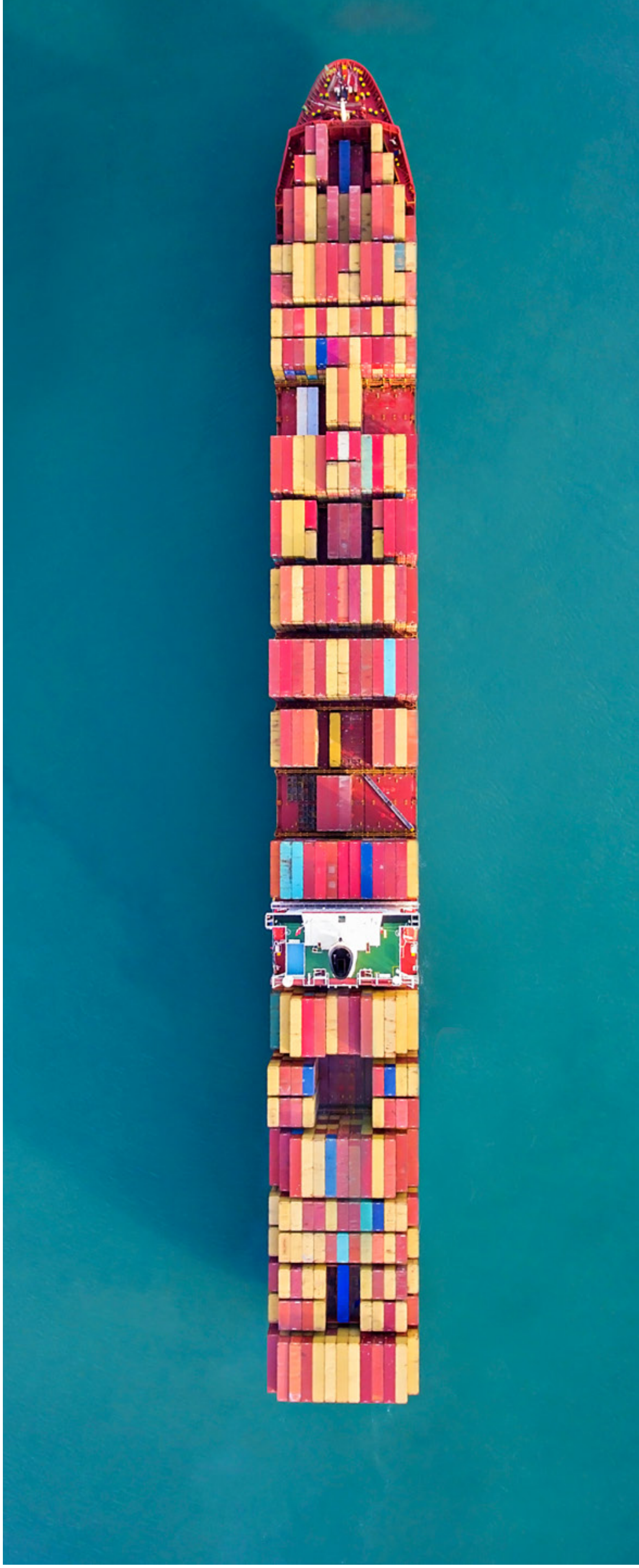
Ships

The number two-emitting heavy transport sector is also shifting course. Marine shipping is the world's sixth-biggest carbon emitter—bigger than Germany. But transparent efficiency data are increasingly differentiating efficient vessels that get chartered from inefficient ones that get idled, then retrofitted or scrapped. New vessels can about double efficiency (or more[97]). Ferries, tugs, and barges are electrifying, many with simple retrofit kits; Norway alone ran more than 30 electric ferries in 2020, doubling in 2021.[98] In early 2021, about 500 electric ships were in use.

Modern sails are sprouting too:[99] as George Dyson points out, freight by sail was highly sophisticated and commercially successful before slower but more-predictable fossil-fueled shipping with lower labor costs displaced it. Transoceanic carriers will also fuel-switch, plausibly to carbon-free ammonia. Maersk, the world's largest shipper, requires all its new ships to accept carbon-neutral fuels; will launch in 2023 (seven years early) the first carbon-neutral container vessel; and plans to cut its operations' carbon intensity 60% by 2030 and 100% by 2050.[100] Such industry alignment on cutting the 6% of oil used and 3% of CO_2 emitted by ships sets an example for other sectors. So does the industry leadership shown in marine shipping's Poseidon Principles.[101]

Summary

In heavy transport as elsewhere, efficiency is not a limited, dwindling, rising-cost resource but an expanding, falling-cost resource: the more you seek, the more you find. This cornucopia is the manual model—one must turn the crank—but a strong arm persistently applied can make three-year-old assessments look conservative. Plummeting costs will speed electrification too as heavy fleets grow, and may unlock early retirements using coal-plant-like financing. So with heavy transport's "hard-to-abate" emissions offering attractive solutions, might industrial heat's CO_2– spurred by demand pull and the new Coalition on Materials Emissions Transparency (COMET)[102]—offer similar surprises?[103]



Industrial Heat

Of the flow of matter in the ~1990 US economy (excluding water returned clean), only 7% got into products and 1% into durable products—of which only 1/50th ultimately returned to create more value.[104] This roughly 99.98% waste may be the world's biggest business opportunity. Producing materials emits one-fourth of global CO_2,[105,106] the biggest threat, and global materials intensity is generally trending upward. That combination is ripe for innovation.

Three sectors dominate. Of the "harder-to-abate" ~35% of global CO_2 emissions, roughly one-fifth comes from making iron and steel, one-fifth from making and curing cement,[107] and one-tenth from making chemicals—60% fertilizers and thermoplastics. Encouragingly, the world's leading makers of steel (ArcelorMittal and China Baowu), aluminum (En+), cement (LafargeHolcim), and readymix concrete (HeidelbergCement, the number two cement-maker), plus many rivals, have announced aggressive decarbonization targets, including long-term net-zero-carbon ambitions.

China's 2060 carbon-neutrality pledge will similarly guide its giant materials industries. And all industries will move far faster to renewable energy, such as green hydrogen (made by splitting water with renewable electricity), where CO_2 emissions are properly priced: \$50/tCO_2 would push green hydrogen into steel- and cement-making, \$100/t by 2050 into nearly 30% of global emissions.[108]

Calcining limestone, reducing iron ore, and steam-cracking hydrocarbons currently need ~1,100°C–1,600˚C "process heat." Most producers focus more on saving heat than on saving electricity,[109] which renewables will make increasingly carbon free. Renewable heat's ~9% share of global heat consumption must soar too.[110] Renewable electricity can efficiently deliver any desired temperature directly or via infrared, microwaves, plasmas, or hydrogen.

BloombergNEF in April 2021 expected solar power in 2050 to be 40% cheaper than estimated two years earlier, making solar- or wind-electric hydrogen remarkably competitive in most markets by 2030 and in all by 2050.[111,112] Alternatively, solar-heated air at 900˚C –1,000˚C has been demonstrated; Heliogen's system will provide process heat for Rio Tinto's borate refinery in California, while CEMEX and Synhelion are building a solar-heated cement pilot plant exceeding 1,500˚C.[113]

High-temperature solar heat with overnight storage like 247Solar's should compete with 24/7 coal or gas heat. Solar troughs producing steam up to about 250˚C cheaper than from natural gas, plus heat pumps amplifying clean electricity severalfold up to 200+˚C, can together match at least a third, perhaps as much as half, of industrial heat use. Some entrepreneurs even deliver renewable process heat as a service: you just tell them how much and how hot you need when.

All substitutions of heat sources get faster and cheaper if efficient equipment, processes, and products need less or cooler heat. Yet many factories do low-temperature tasks with ~2,000+˚C flames—"like cutting butter with a chainsaw."[114] In contrast, Tesla's solar-powered, zero-combustion battery-making Gigafactory got its Nevada air permit in a half-hour, not six-plus months, then met its biggest process heat load not with 1,000 gas-fired kilowatts but with one 15-kilowatt electric heat pump delivering solvent redistillation's needed temperature difference—just 1.5C˚.

Exhibit 4 Retrofit Energy Savings and Newbuild Savings from Redesigning Industrial Facilities

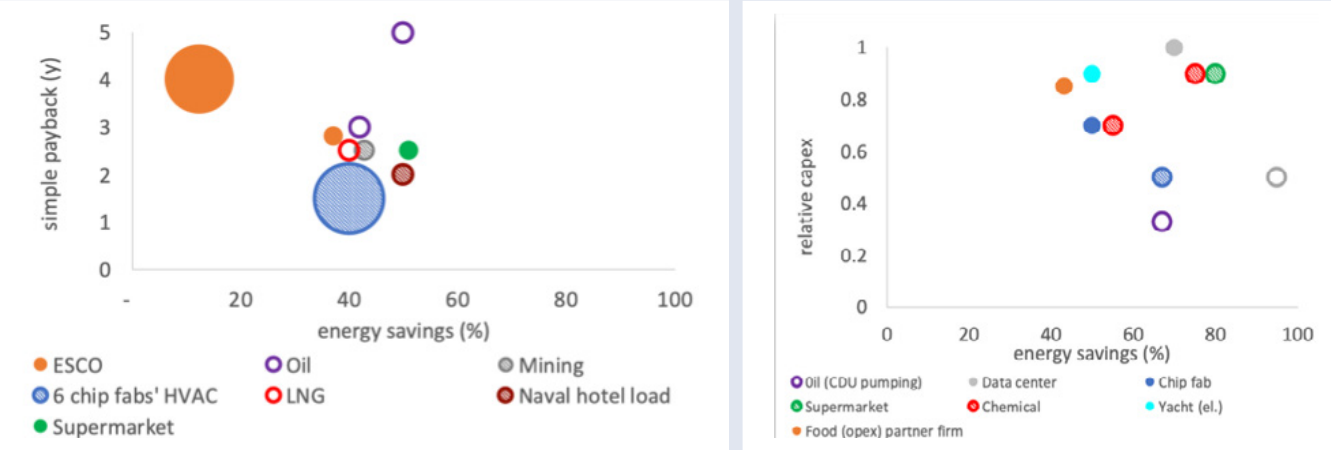


Image credits: courtesy RMI/LALLC

Retrofit (left chart) can cut energy use by about 30%–60% and newbuild (right chart) can save about 40%–90+% as designed or measured in RMI's redesigns of diverse, generally large, industrial facilities worth a total of more than $50 billion.[115]

Solid dots are built projects, open circles are not yet built, shaded dots have incomplete data, and bubble sizes have no significance. CDU refers to a refinery's crude distillation unit. The retrofit graph's large brown dot approximates typical performance by energy service companies delivering dis-integrated design. The small brown dot averages 62 projects in 2017 in 22 countries by one of the best ESCOs (Crowley Carbon) with 37% primary energy savings and 2.8-y average payback—optimized and sustained by monitoring and diagnostic software absent in most RMI retrofits, so combining packages should improve both that ESCO's results and RMI's.

Integrative design also saves far more energy than normally assumed, and at lower cost, in producing and fabricating materials, including those (like chemicals) not explicitly treated here. The potential for saving fossil fuels and electricity in diverse industrial processes is illustrated by empirical design results (Exhibit 4) from several decades of RMI's practice.

Saving, preserving, and recovering heat remains imperative—especially for cement, where conventional decarbonization could double price per ton and dominate the total abatement cost of the "big three" sectors.[116] Classical industrial heat-saving,[117] often slow, could get leapfrogged as microfluidics, synthetic biology,[118] and new catalysts[119]—enormously sped by light, electricity, or tuned vibrations—retire chemistry's old high-temperature reactions.[120,121] But even bigger solutions hiding in plain sight save energy-intensive materials via two expanding and surprisingly neglected menus[122,123]: a more-circular economy (saving up to 37% of steel, 34% of cement, 40% of aluminum, and 56% of plastics[124]), plus wide, deep redesigns and substitutions only starting to be explored. Materials we don't use need no energy to make or move.

Saving Energy-Intensive Materials

Even if making ammonia at ambient temperature and pressure—a revolutionary prospect now in the lab—came to market, or if wind-powered hydrogen took over conventional production,[125] precisely applied synthetic nitrogen fertilizer would still make soil emit more nitrous oxide (a potent greenhouse gas), not make agriculture durable. Emulating natural systems—not treating soil like dirt—appears to offer similar or better yields, comparable co-benefits, health, and resilience, and a sounder social and business model.[126]

Plastics' ~$350 billion/y externalities should motivate frugal and judicious use and reuse.[127] Refineries may replace distillation with membranes, but electric vehicles need no refineries. Steel and cement could devour half the world's remaining carbon budget (to 2060, for 50% odds of limiting global warming to 1.5C°)[128] if today's wasteful construction methods and emissions-intensive manufacturing processes endure—or could lucratively transcend them. The following gallery of opportunities focuses on buildings and autos, together responsible for half the CO_2 from steel, aluminum, cement, and plastics.[129] Buildings alone use half the cement and over one-third of the steel.[130]

In 2019, the International Energy Agency found a 2060 technical potential to save about 82% of steel and 90% of cement by systematic and comprehensive gains in materials efficiency across the value chain.[131] This bonanza was without even analyzing many opportunities covering half of steel and cement use and two opportunities covering all cement use. Nearly half of that impressive 5X–10X materials-saving technical potential was found practical, totaling 39% of business-as-usual steel use and 38% of cement. Now let's explore why the practical potential could actually be much larger than those impressive and authoritative estimates.

Iron and Steel

The world makes 3,500 grades of steel totaling more weight than any other manufactured material, but its dominant (and dirty[132]) blast furnaces are losing favor: electric steelmaking is common, renewable-hydrogen steelmaking is emerging, and both are shedding cost as renewable power drops below 2¢/kWh. Swedish-piloted hydrogen-based CO_2-free primary steelmaking (targeting scaleup to 5 million tons/y by 2028[133]) would cost about 20%–30% more with 4¢/kWh–5¢/kWh Northern European clean electricity, but not with cheaper renewables elsewhere. Instead, hydrogen-based CO_2-free primary steelmaking could achieve a fully loaded $400/t, matching many existing fossil-fueled steel mills. This requires 2.5¢/kWh renewable electricity, already common, powering $450/kW electrolyzers, around today's best price but likely to halve in this decade.

With lower capital cost and no coking coal, new green steel mills, say at or near Australian iron-ore mines as Fortescue Metals Group plans, could strand today's assets as swiftly as basic oxygen furnaces with similar economic advantages dropped open-hearth steelmaking's US capacity share from 90% to 10% in 20 years.[134,135] Moreover, with steel as with other materials, materials cost is enormously diluted by other costs, contributing only slightly to the cost of finished goods, so even substantially costlier green basic materials would scarcely affect consumers.[136]

Steelmakers' average energy intensity has halved since 1950 (though only by just over 10% in the past 25 years), with tens of percent to go. But how efficiently steel is used is twice as important.[137] Steel is used half for construction[138] (of which 64% is for buildings and 34% is for infrastructure) plus industrial equipment (16%, four-fifths mechanical), vehicles (13%, half autos), and miscellaneous (18%). Astonishingly, as we'll see next, much if not most steel is wasted, so a green steel industry could need far less capacity and production than exist today, needing less investment and less time to build it. Where are these vast steel savings?

In buildings, better-designed beams and columns can safely save at least 45% of their structural steel and 15%–30% of their rebar;[139] indeed, as noted below, the supported weight can often be about halved, and steel rebar can often be advantageously eliminated by noncorrodible substitutes (or simply by better concretes). Three leading structural engineering firms confirmed in interviews that they can typically save half the concrete and steel normally used in structures —about 20% by correcting common sloppiness and roughly 30% by better design and materials.[140] (Savings are far bigger in countries where prudent builders guard against corruption or poor quality by doubling steel rather than focusing on project management.)

Efficient use of automotive sheet steel could save one-fourth its emissions and costs,[141,142] while normal steel lightweighting and substituting aluminum could annually save about 1 gigaton (Gt) of CO_2 by 2050, then more by enabling fuller recycling.[143,144] With more difficulty but greater rewards (two-thirds of US autos' fuel use is caused by their weight[145,146]), switching to carbon-fiber composites could cut a typical auto's iron and steel content by 90% or nearly 1,700 kg[147]—3X normal assumptions, and China targets 79% by 2030.[148] This offers huge indirect benefits,[149] including roughly 2X–3X savings on propulsive energy, battery sizing, and recharging investments (Exhibit 5).

As noted above, BMW's profitable carbon-fiber-bodied electric i3 disproved conventionally assumed higher cost in 2013; its lightweighting was approximately free.[150] IEA assumes only 40% lightweighting by 2060, yet finds that total steel demand to make autos, instead of rising 20% in 2017–60, could fall by 85% as materials substitutions combine with efficiencies in producing and fabricating steel.[151] Either way, largely steel-free vehicles are just the start of multiplicative shifts. A lucrative vehicle-sharing business model could cut 70% off the 2050 CO_2 embodied in EU autos' materials.[152] Autos are also the second-biggest household asset in most developed economies, yet sit ~95% idle—an irresistible target for diverse IT-based monetizers of idle assets, like Uber and Lyft—not to mention new-urbanist design, virtual mobility, and desubsidization that could slash the need to drive, let alone to own a personal vehicle.

Exhibit 5 Current and Upcoming Efficient Cars

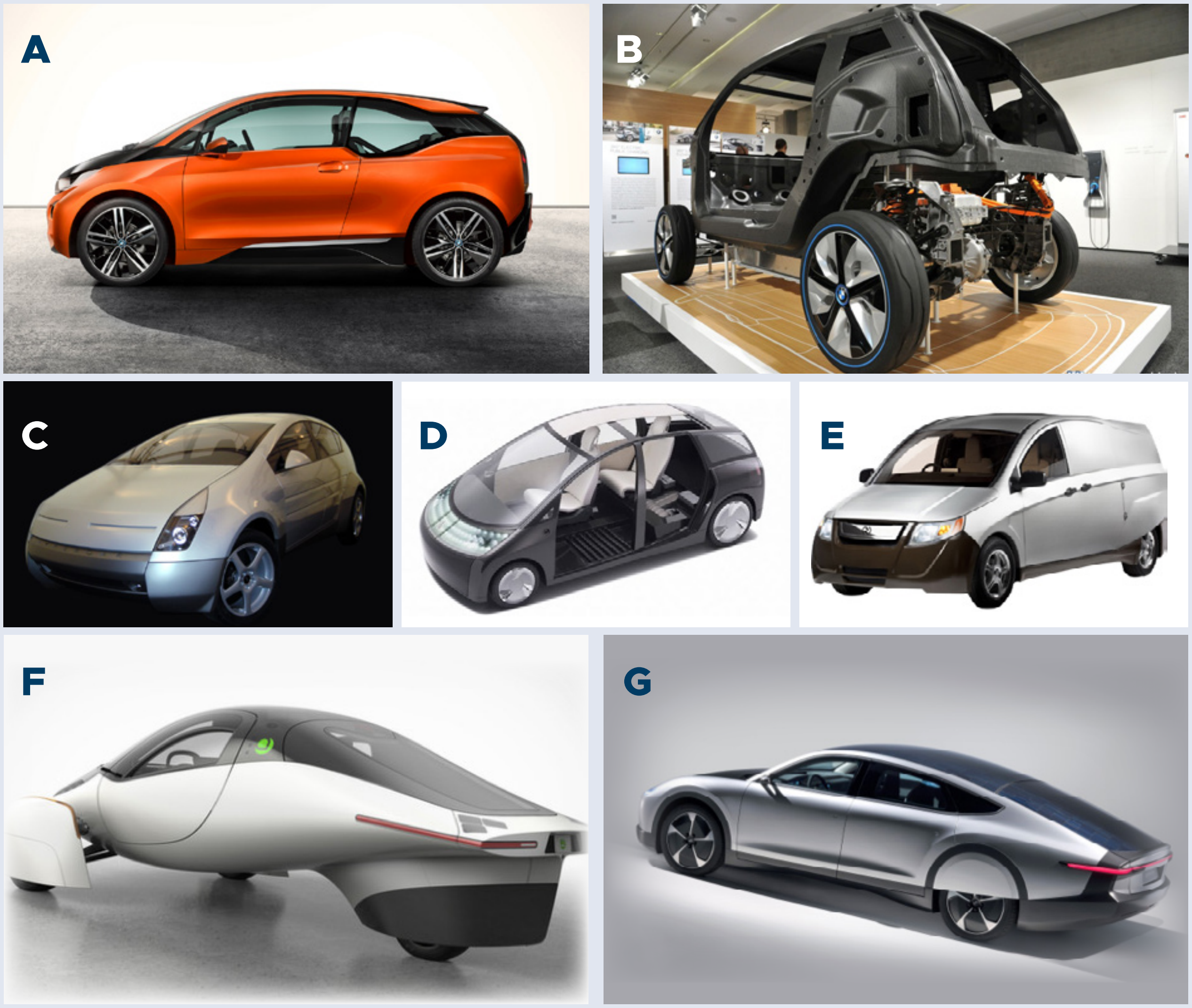


Image credits: a: courtesy of BMW Press, b: courtesy of BMW Press, c: RMI, d: courtesy of Toyota, e: RMI, f: courtesy of Aptera, g: courtesy of Raoul Cooijmans with Lightyear

Steel-dominated autos face competition from innovations like BMW's 4X-efficiency 2013–24 i3 (a). The extra cost of its body's carbon-fiber composites (b) was offset by integrative design,[153,154] validating claims for a 4X–6X-efficiency carbon-fiber SUV design (c) done in 2000.[155] Toyota's 2007 1/X carbon-fiber concept hybrid (d)—400 kg with Prius volume and powertrain—demonstrated 70% lightweighting. Even the 2009 aluminum-dominated Bright IDEA prototype hybrid utility/delivery van (e) saved a ton and most of its batteries, offering 3X–12X efficiency at competitive cost. Next, taking aim at recharging infrastructure by roughly doubling Tesla Model 3 efficiencies, two light, low-drag electric vehicles powered largely or wholly by their topside solar cells[156]—the 343-mpge two-seat composite Aptera (f) and 251-mpge five-seat mainly-light-metal Lightyear One (g)—are planned for late-2021 initial production. And even without such integrative design, carbon-fiber costs could soon reach levels at which they can displace ~1–2 tons of iron and steel per auto—especially if automakers count cost not by the kilogram or part but by the car, the way we buy them. The era of the two-ton steel car is drawing to a close.

Light Metals

Aluminum use has soared 30X since 1950 and causes ~3% of "harder-to-abate" or 1% of total CO_2 emissions. Its energy inputs are roughly one-third heat and two-thirds electricity. Like pulp and paper, its CO_2 is relatively easy to abate. Over half the smelting is in China, mostly powered by inefficient captive coal plants with more capacity than Germany's coal plants.[157] Shifting to renewables should be sped by the London Metal Exchange's proposal to label and trade low-carbon aluminum from 1H2021.[158,159] Smelters can also valuably help balance the grid.

Elysis, an Apple-backed Alcoa-Rio Tinto joint venture, has demonstrated ceramic replacements—carbon-free and 30X longer-lasting—for carbon anodes, eliminating process CO_2 emissions. Audi will use that product for aluminum wheels, while BMW will use Emirates Global Aluminium's CelestiAL metal smelted with solar electricity. Analogous process improvements continue with magnesium and titanium.

Light metals' premium value in electric vehicles, where the metals' saved weight offsets heavy and costly batteries, is increasing their use.[160] So are new casting methods, alloys, and forms. Recycling's huge energy savings rise with 3X–5X-more-efficient remelting methods,[161] heat-saving ways to refine bauxite into alumina (commonly at 145°C–265°C, easily solar), and avoiding process losses that mean "around half of all liquid aluminum never reaches a final product."[162]

Cement and Concrete

The world's four billion tons of cement per year are comparable in mass to global food production. Cement's CO_2 emissions are 7%–8% of the global total, and like steel's, exceed those of any country except China and the United States. Half the cement binds sand and gravel to make concrete; the rest makes mortar, plaster, and blocks. Half the cement ends up in buildings, half in roads, bridges, and other infrastructure. At least 70% of the total CO_2 from making concrete comes from making the roughly 10% of its mass that is cement—not including CO_2 gradually reabsorbed later ("carbonation," discussed below) as the cement partly reverses the reaction that released the CO_2 by calcining limestone.[163]

Traditional remedies start by making Portland cement with less, cooler, and cleaner heat,[164,165] and by adopting proven substituents (like fly-ash, slag, and burned rice hulls), aerated mixes, biocements, and alternative supplementary cementitous materials like calcined clays and mechanically activated pozzolans[166,167] (which can cut CO_2 52%–70%[168]).

These changes in the composition of concrete are simple, quick, and powerful. Concrete's cement content can vary up to threefold without affecting performance, so thoroughly optimizing concrete mixes and constituents could save up to 50% of CO_2. That includes roughly 15%–30% just by global adoption of limestone calcined clay cement, and correcting sloppy practices that can waste over half the cement in poorly run concrete-block factories and construction sites.[169]

A third of LafargeHolcim's 2019 net sales were from a portfolio of 23 green solutions including ECOPact, which offers 30%–100% carbon reductions, or even more by adding circularity options. A deeper opportunity, but slower—because the construction sector is fragmented, sluggish, and deeply risk-averse—is novel cement chemistries.

Solidia's lower-cost low-calcium patchable cement, marketed with Lafarge,[170] saves 50%–70% of CO_2 emissions for nonreinforced precast products (under 10% of the market, but potentially rising to 30% as corrosion-resistant reinforcement is demonstrated), 15%–25+% for the ready-mix remainder. The firm's lab-scale gamechanger, with better properties and perhaps lower cost, cures not with water or CO_2 but with carboxylates such as oxalates (makeable from CO_2 and renewable electricity). Then instead of emitting approximately 1.5 carbon atoms per calcium atom (1 from calcination, about 0.5 from fuel), cement could sequester 2–4 gross or 0.5–2.5 net, making cement a major net carbon sink.[171,172]

Carbon-negative competitors like Carbicrete, biocements made at room temperature,[173] and even electrochemical cement-making processes are emerging.[174] An unreinforced compressed concrete with just 4%–5% polymeric binder, displacing all conventional cement, is claimed to be cheaper and stronger than typical steel-reinforced concrete.[175]

Saving Materials

Complementary and even more powerful is to need less,[176] use other, use less,[177] use longer,[178] use again,[179] and align incentives. "As much as half of the solution may be changes to how concrete is specified and used;" optimizing EU cement use could in principle provide the same 2050 services using 65% less cement by designing out both excessive cement and wasted concrete.[180] Saving concrete usually also saves its steel reinforcing bars (rebar): in very high-rise buildings, thinner columns made of very-high-strength concrete can save up to 50% of the steel reinforcement too. Saved tons of concrete multiply by saved tons of cement per ton of concrete (up to 3X as noted above) and by saved CO_2 per ton of cement. The more you decompose these terms, the more granular and cumulatively large the opportunities you discover.

Savings multiply further if we delve into root causes: do we really need all that stuff made of cement? The remote infrastructure providing six kinds of services to new buildings can often be replaced by on-site techniques saving the concrete and steel in the infrastructure and all the pipes and wires in between,[181] at lower cost to society and probably to developers. Making impervious landscape spongy can manage stormwater without concrete drainpipes.[182] Replacing separate specialized buildings with multipurpose and mixed-use can save structures and travel. Additive manufacturing, such as 3D printing, enables airy bone-like structures using no factory and little metal, and if done locally, can save steel vehicles and concrete-and-steel roads and warehouses.

Microreactors etched into stacked silicon wafers may control chemical reactions so precisely that they make only pure product, eliminating the 80%–90% of many chemical plants (made of concrete and steel) devoted to separating unwanted byproducts. Shared and connected mobility saves roads and parking. So does virtual mobility that ships electrons and leaves the heavy nuclei at home. And designing cities around people, not cars, can save one-third of concrete and two-thirds of driving while improving quality of life. These savings often compound.

Mobility-as-a-service in 2019 had 50 million drivers serving a billion ride-hailers who wanted to go somewhere, not own a vehicle. The analogous solutions-economy business model[183]—one of five strategic innovations discussed in the companion paper ("Trucks, Planes, and Steel: Decarbonizing the Toughest Sectors")—can lease structural performance rather than selling tons of cement and steel, so the provider and customer both make more money from fewer tons. Both parties' interests are aligned on doing more and better with less for longer. The provider can also reward structural engineers for delivering the best performance with the least material.[184] When I suggested this a few years ago to the head of a giant cement company, he replied, "Good idea. I have 200 people working on that right now."

Structural Efficiency

Rewarding elegantly frugal design may even wring up to an order of magnitude more work from cement and steel—not just the roughly 20% conventionally assumed—by exploiting two partly overlapping opportunities. The first is that materials-efficient design is rarely requested and even more rarely rewarded,[185] so engineering culture and practice routinely tolerate and even extol grossly excessive design margins, often severalfold beyond reason.[186] The second is that even when [rarely] optimized, conventional practice adopts traditional, familiar, comfortable designs.

The literature underlying the Energy Transitions Commission's (ETC's) *Mission Possible* report appears to overlook novel but proven structural concepts that exploit established engineering concepts in different and more original ways to achieve dramatic materials savings. These powerful design shifts combine with traditional design optimizations and the new materials and other system improvements described above. Yet even IEA's valuable 2019 analysis assumes only 13% savings from structural optimization,[187] then applies it sparingly and only to non-precasts. The following vignettes illustrate a far larger overlooked potential.

Substituting tension for compression structures (Exhibit 6a and 6b) improves strength, esthetics, and cost with typically ~80%–90% fewer tons. Shell, fabric, and cellular structures (like Exhibit 3) offer spectacular savings.[188] Fabric forms' optimal shapes can save at least half the concrete in beams (6c), sheets (6d), and other common cast-concrete shapes, all with the same or better performance.[189,190] Concrete slabs can be carefully thinned by 75%–80%[191] (6j and Exhibit 7c below) or replaced with lighter wood. Twisting the 128-story Shanghai Tower (Exhibit 6m), the world's second-tallest building, shrank wind loads and their structural systems 24%, cutting materials costs by $58 million.

Weight savings snowball because you need less strength to hold up less weight. That helped New York's Freedom Tower (Exhibit 6l) save 40% of its cement with a concrete mix 6X stronger than garden-variety; today's best is over 2X stronger still. Bridges too hold up mostly their own weight, but airy and robust concrete bridges can be 3D-printed (6h), like a swooping stainless-steel bridge built for Amsterdam (6i). More-uniform cement quality reduces the quantity needed to ensure performance—by ~3X when China switched from poor-quality shaft kilns. And concrete use per square meter of floor space rises steeply with height—by 20% going from 3 to 10 stories, or 50% going from 3 to 15[192,193]—so lower buildings with new-urbanist layout can help. Just the novel 3for2 design (Exhibit 7d below) also reduces height by one-third for the same floor space and ceiling height.

Superstrong bulk materials can weigh almost nothing: in Exhibit 6k, TU Berlin's structural engineering faculty stands on a 13-meter free span supported only by three carbon-fiber ribbons one millimeter thick. A thin carbon-fiber sheet can save two-thirds of the wood in a glulam beam or 30%–50+% of the concrete in a structural panel. Carbon-fiber anticorrosion wraps (6e) save the 30%–40% of concrete that adds weight but not strength, merely covering the corrodible steel rebar to protect it from rusting. Carbon (6f), fiberglass, or basalt (6g) rebar eliminates that steel.[194,195] So does carbon-neutral bamboo-concrete where suitable,[196] or carbon fiber used instead of steel strands to prestress slabs (6j and 7c), or the more bendable polymeric concrete mentioned above.

Eliminating corrodible mild-steel rebar (or reliance on anti-rust coatings that can chip or fail) also brings another big benefit. In the roughly 20% of global construction sites that are rainy or humid, designers seek to block or slow concrete's gradual absorption of CO_2, lest the less-alkaline moisture in the concrete corrode steel rebar, risking structural failure. Most designers do this in the dominant drier climates too. But without steel rebar, designers could instead ease and speed beneficial carbonation and thus help future concrete, even with traditional composition, to reincorporate approximately 20%–25% of the process CO_2 released into the atmosphere when originally making the cement.[197,198]

Exhibit 6 Examples of Structural Efficiency

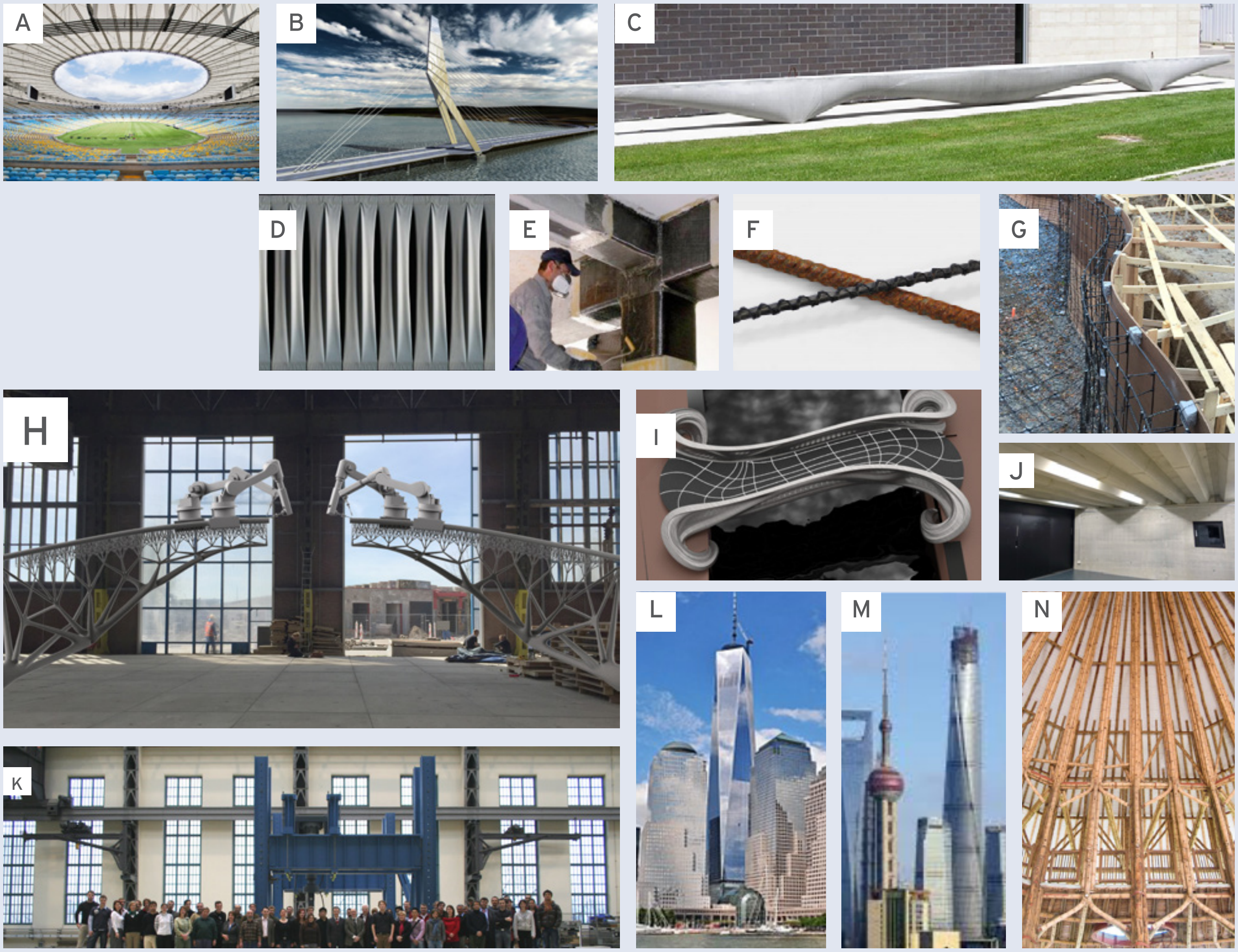


Image credits: a: © Marcus Bredt, b: © sbp/Mathias Widmayer, c: courtesy of Matt West, d: courtesy of RP Schmitz, e: Mapei SpA, f: courtesy of SGL TECHNOLOGIES GmbH, g: courtesy of Smarter Building Systems, h: MX3D Bridge, design by Joris Laarman Lab, i: MX3D Bridge, design by Joris Laarman Lab, j: garage of a residential house, Berlin, Germany, © Mike Schlaich, k: courtesy of Achim Bleicher, n: courtesy of Amory Lovins

Lower-cost, materials-frugal tension structures (a,b) can cut materials use ~80%–90%. Fabric-form beams (c), sheets (d), and other cast-concrete shapes save 50+% by putting material only where it's needed. Carbon-fiber wraps save nonstructural cover concrete (e) to protect steel rebar, which carbon-fiber (f, compared with steel), glass-fiber, basalt (g), or bamboo reinforcements eliminate.

3D printing can make an ultralight dendritic bridge (h, a rendering) or a real stainless one (i). Craned-in folded 4-cm carbon-reinforced concrete roof slabs replace 30 mm flat slabs for 80% materials savings (j). Three carbon-fiber ribbons 1 mm thick support a 13-m span (k).

New York's 541-m Freedom Tower saved 40% of its high-performance cement (l); the 632-m Shanghai Tower cut wind load structure 24% by twisting (m). Simón Vélez's 2,150-m^2 polygonal bamboo pavilion (n) built with hand tools by Colombian peasants used only 5% metal and 15% concrete, yet met German building codes.

Natural composites, notably wood and bamboo can also turn CO_2 into complements or replacements for steel and concrete. Cross-laminated timber is replacing concrete floor slabs and beams, while beautiful, fire-safe, lower-cost, all-wood buildings move from midrise to high-rise.[199,200] Some new wood towers are taller than 80 meters, with a 350-m 90%-wood tower planned in seismic Tokyo. A remarkable handmade bamboo pavilion 40 meters in diameter, 14.4 m high, with 7-m roof overhangs was transplanted to the Hannover Messe and earned its Colombian vernacular builders German Baumeister (Master Builder) certificates. Its 500-metric-ton total mass included 100 tons of bamboo, 75 of concrete, and 10 of iron and steel (Exhibit 6n).[201]

Revolutionary, or rediscovered ancient,[202] design frugality, if allowed by analytic methods and building codes, can transform even mundane and ubiquitous uses like the common reinforced-concrete floor slab. That flat slab limits sagging by compressing its top surface while stretching its bottom surface, but concrete has little tensile strength, and most of the concrete and steel are wasted deadweight. In contrast,[203] a shallow thin-shelled dome, stiffened by thin ribs placed only where needed and rising to a flat upper surface (Exhibit 7a), bears its load solely through compression. This saves up to 70% of the concrete and all the steel—eliminating more than one-third of the building's total structural mass, plus further weight in columns, footers, etc.[204]

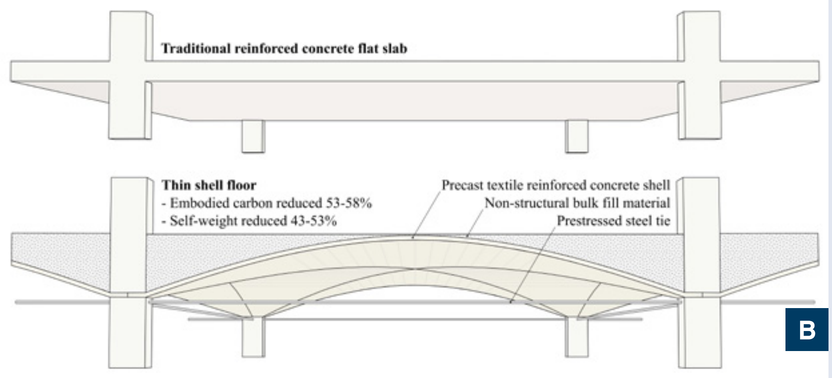
A fiberglass-reinforced vaulted thin shell (7b) also shows impressive properties, potentially saving 64% of mass and 62% of embodied energy for a single floor.[205] Even a vaulted 2-cm unreinforced concrete floor looks promising.[206,207] Three vaulted masonry buildings thus had 4X–10X less embodied carbon intensity (CO_2e/m^2) than the average of 600 typical concrete-and-steel ones.[208]

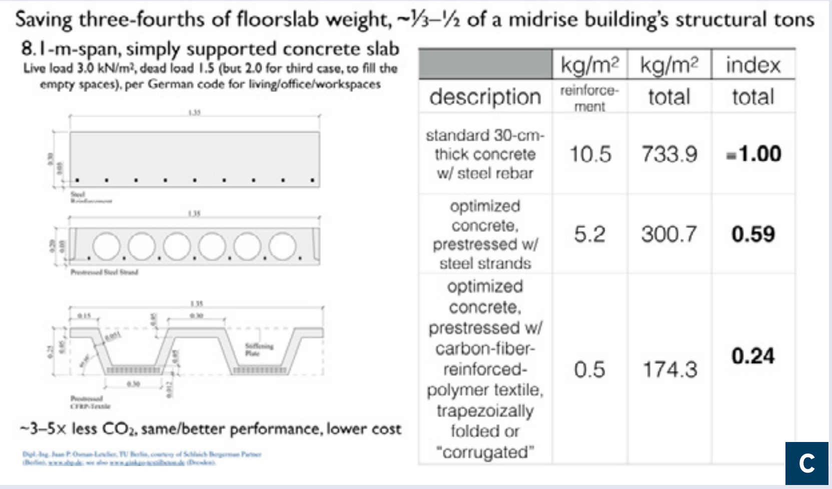
Alternatively, a folded thin slab (7c, like Exhibit 6j but with live loads) uses corrugated geometry to save 76% of the concrete and all the steel.[209,210] And designing out the traditional 1–1.5 meter-high mechanical plenum between floors in a mid- or high-rise building (7d) can fit three stories into the height of two without reducing ceiling heights. This saves more than 15% of structural core mass, 9% of glazing, and ~77% of energy in a high-rise, with faster build, 5% more rentable space from distributing mechanicals, and more stories or a shorter building.[211]

Further materials-saving design opportunities not illustrated here include layouts that reduce perimeter walls, terraced rather than single detached housing, and even, as in my house, recurving walls with greater strength and stiffness (plus seven other benefits). Similarly, gently curving the long axis of RMI's Innovation Center bent its straight roof beams into shallow sideways arches that compressionally resist lateral wind loads without needing traditional X-bracing.

Fractally at every scale, we can imitate nature's mass-efficient designs, from trees to bird-bones.[212] We can also imitate materials designs like the abalone's otter-resistant shell—tougher than our best missile-nose-cone ceramics, and made not in an incandescent furnace but by self-assembly in 4°C seawater. Conch shell is 10X tougher still—1,000X as tough as the chalky mineral it's made of. Sea-urchin spines' self-assembling mesocrystalline structure achieves 40X–100X concrete's bending strength. What could we do with that?

Exhibit 7 Strength through Geometry





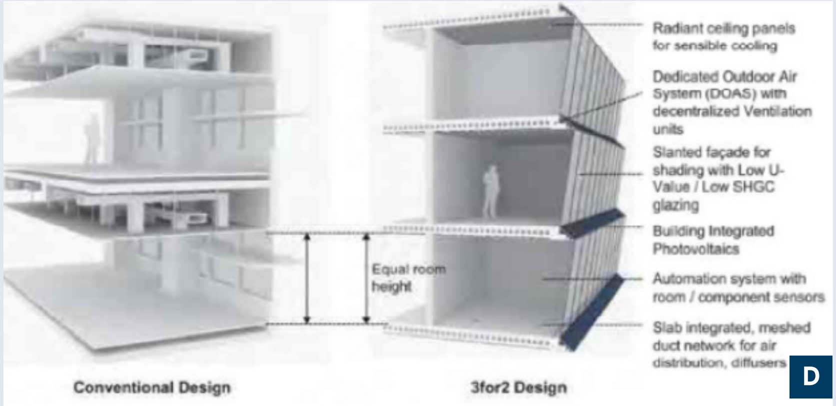
Saving three-fourths of floorslab weight, ~⅓–½ of a midrise building's structural tons

8.1-m-span, simply supported concrete slab

Live load 3.0 kN/m², dead load 1.5 (but 2.0 for third case, to fill the empty spaces), per German code for living/office/workspaces

	kg/m²	kg/m²	index
description	reinforcement	total	total
standard 30-cm-thick concrete w/ steel rebar	10.5	733.9	**≡1.00**
optimized concrete, prestressed w/ steel strands	5.2	300.7	**0.59**
optimized concrete, prestressed w/ carbon-fiber-reinforced-polymer textile, trapezoizally folded or "corrugated"	0.5	174.3	**0.24**

~3–5× less CO_2, same/better performance, lower cost



Elegant "strength through geometry" ways to save up to 70% (a) of concrete floor-slab mass, which is about half the total structural mass of multi-story buildings, by replacing a thick rectangular slab with a thin vaulted arch, built up to a flat top with stiffening ribs, plus exterior tensioning cables beneath the corners. Alternatively, using similar principles (b), textile-reinforced thin concrete shells permit vaulted floors saving 53%–58% of embodied carbon and 43%–53% of their own weight (plus savings in supporting structures) with 6–18-m spans.

(c) A 4X lighter floor-slab (or 5X lighter roof-slab as in Exhibit 6j) results from prestressing well-chosen concrete with carbon-fiber rovings, not simply reinforcing it with steel rebar, and precasting it folded trapezoidally to gain stiffness like corrugated cardboard. (d) The "3for2" design in these conceptual schematic sections, proven in Singapore in 2015, vertically condenses buildings by one-third by replacing mechanical plena between the floors with distributed and integrated building systems, with great economic advantage and more than 15% savings in concrete and steel.

Image credits: a. ETH Zurich, Block Research Group / Photograph by Nick Krouwel, b: courstey of Will Hawkins, c: courtesy of Juan Pablo Osman Letelier, d: courtesy of CTBUH

Project supported by Siemens and Singapore ETH Centre Future Cities Laboratory

Summary

IEA's finding of a technical potential to save ~82% of steel and ~90% of cement—despite underscoping structural-design opportunities by manyfold (Exhibits 6–7) and road-vehicle savings by at least twofold (Exhibit 5)—could plausibly be much more nearly approached by including such opportunities not previously synthesized or widely understood.

To be sure, high-strength steels and concretes do cost more but save money overall. Smart design costs less than the materials it saves: discriminating executives who insist on top-quality design gain competitive advantage by beating commoditized "infectious repetitis." Saved materials need less supply-side decarbonization and produce profits to offset decarbonization's costs where it's still needed. Each overlooked benefit or misaligned incentive invites a new business model.[213]

Important 2018 assessments variously projected 2050 materials-efficiency savings of 20% of steel,[214] or in principle 20%–30% of cement and steel in buildings.[215] Yet for EU building materials efficiency they apparently adopted just 12% for steel and 14% for cement, scaling globally to about 9% and 11%.[216] How much more now looks practical and profitable?

The menu of materials savings just illustrated is so rich and rapidly expanding that it implies a scope for far higher ambition: at least by a factor of two just from well-executed structural efficiency. It even approaches an order of magnitude (a factor of about ten) when combined with alternative materials, more-efficient production processes, cleaner heat, and circularity. Fully used, this suite may rival clean electricity's industrial decarbonization potential. Its benefits justify strenuous efforts to speed and raise the already-important projected 30% saving (1.2%/y) in materials and energy.[217]

Like everything else in energy, revolutionary change emerging in heavy industry makes three-year-old assumptions ripe to reexamine. Since respected assessments like the ETC's 2018 *Mission Possible* report, the solar and wind share of global electricity has doubled while its grid-integrated cost has more than halved.[218] In a few years, will this paper's snapshot of heavy transport and industrial heat look similarly conservative?

And by the way, heavy transport and industrial heat interact: better Chinese cement needs less transport and infrastructure (trucks, trains, roads, bridges), boosting its direct CO_2 savings by another 10% or so. Saved materials beget more savings. Easier savings enable harder ones: cellphone batteries enable car batteries whose scaling and refinement enable truck and airplane batteries whose cheapness and ubiquity also speed renewables' takeover of electricity. Savings multiply across time, space, and sectors.

Conclusion

These expanding opportunities, both old and new, make heavy transport and industrial heat look not uniquely hard but differently hard. Of course, none of this is easy, and subsectors like cement have unique institutional blockages. Policy, public, and investor push—plus big demand pull[219]—must vault a daunting array of barriers. Yet the "hard" sectors' concentrated big players and large, high-duty combustion devices; operators' relentlessly competitive focus on the business case;[220] heavy trucks' fast stock turnover;[221] and innovative financing (like the methods now gracefully retiring uneconomic coal plants) might even add up to potential decarbonization advantages over messier, fragmented-market, multimillion-target, ponderous sectors like light-duty vehicles and buildings.

Not every idea will work, but for society (subject to equity and political economy), profits from some may offset losses on others. Public policy increasingly provides strong tailwinds. And we're off and running: 2020 investments in decarbonizing the global economy—renewables, beneficial electrification, hydrogen, and carbon capture and storage—were a half-trillion dollars, plus energy efficiency ($0.22 trillion) and materials efficiency.[222]

So in the end, will decarbonizing "harder-to-abate" sectors be costly as widely assumed (albeit unimportantly so for buyers of final goods and services[223]) or profitable? Heavy transport is dominated by trucks, where electrification clearly wins;[224] likewise in buses and most trains, though some are adopting green hydrogen. Aviation comes next, with electrification likely to win in short-hauls, battle biofuels and hydrogen for mid-hauls, and make green hydrogen for long-hauls (with possible superefficient wildcards). But any higher fuel costs could be swamped by the 3X–8X aviation efficiency leapfrogs already known, reducing overall costs while expanding the scope for electrification.

In marine shipping, efficiency can likewise dilute and offset initially costlier clean fuels like ammonia or hydrogen, but the trajectory of green hydrogen means long-run clean fuel prices will probably beat oil. And in both aviation and shipping, unbundling carbon-free from other fuel attributes opens useful avenues for creatively managing costs. In sum, today's twin revolutions in vehicle efficiency and fuel cost make it hard to see why decarbonized heavy transport should cost more than today's—even ignoring the important potential for virtual travel, repatriated manufacturing, smart logistics, and intermodal shifts to reduce the need for transport.

Industrial heat is even more complex in detail but perhaps as simple in outline. About three-fifths of this sector's CO_2 is from steel and cement. Both are at least half wasted by inferior structural design correctable by design-practice, client-education, and business-model changes that are clearly challenging but should cost far less than the avoided materials usage. Alternatively—using conventional design—a combination of precasting, fixing construction-site waste, and correctly specifying and using the right kind and amount of cement can profitably save a comparable amount. These two approaches overlap substantially, but where they don't, they're not mutually exclusive.

Circularity too is additional (actually multiplicative), expanding, and increasingly profitable. Exploiting concrete carbonation in drier climates (for free) and eliminating rebar corrosion risk in wetter ones (profitably expanding current carbon-fiber substitutions as carbon fiber also heads for green production) could add an important new CO_2-mitigating, structural-risk-reducing, and steel-saving term.

Traditional starting-points in decarbonizing basic materials—saving heat, cleaner heat sources, smarter processes, more substituents, and novel products—are a complex mixture of costlier, breakeven, cheaper, and in expected or hoped-for transitions along that axis. But earlier analyses weighted chiefly toward that conventional portfolio and its continued improvements seem qualitatively to be headed for a major tilt toward profit as the greatly underweighted materials-productivity opportunities come to the fore and more than offset any higher materials costs.

The potential to save roughly half, not a tenth, of cement and steel just by comprehensively overhauling civil and structural design, with careful construction practice, is perhaps the biggest gamechanger that appears semiqualitatively adequate to flip the whole materials story from cost to profit: immense materials savings should reduce project cost more than smarter design and greener materials increase it. Lower-temperature industrial process-heat needs, too, are generally in range for profitable electric heat pumps or increasingly competitive solar process heat. Add it all up, and it's hard to make a convincing case that this decarbonization slate, advancing as it scales, won't be profitable.

This adds economic strength to the climate case for rapidly and gracefully retiring $20+ trillion worth of dirty assets (Exhibit 8), financing their clean replacements, and speeding capital flight from obsolete to advantageous assets and industries. Little climate headroom remains, so today's imperative is out with the dirty and in with the clean—urgently. That's especially complex in China, which holds nearly half the critical assets (notably blast furnaces and cement kilns) within a political economy juggling air quality and health with local jobs and influence.

In global electricity, until 2018 renewables augmented rather than replaced fossil-fueled generation, but now coal power is plummeting and gas power has turned bearish (costing GE three-fourths of its market cap in two years). Next, efficient vehicles, clean industries, and structural materials efficiency could retire dirty production faster, especially in cement and steel, just as efficient electrification can speed the renewable takeover of the power sector. What's more, those two revolutions can build on each other.

Exhibit 8 Committed Emissions from Existing Energy Infrastructure

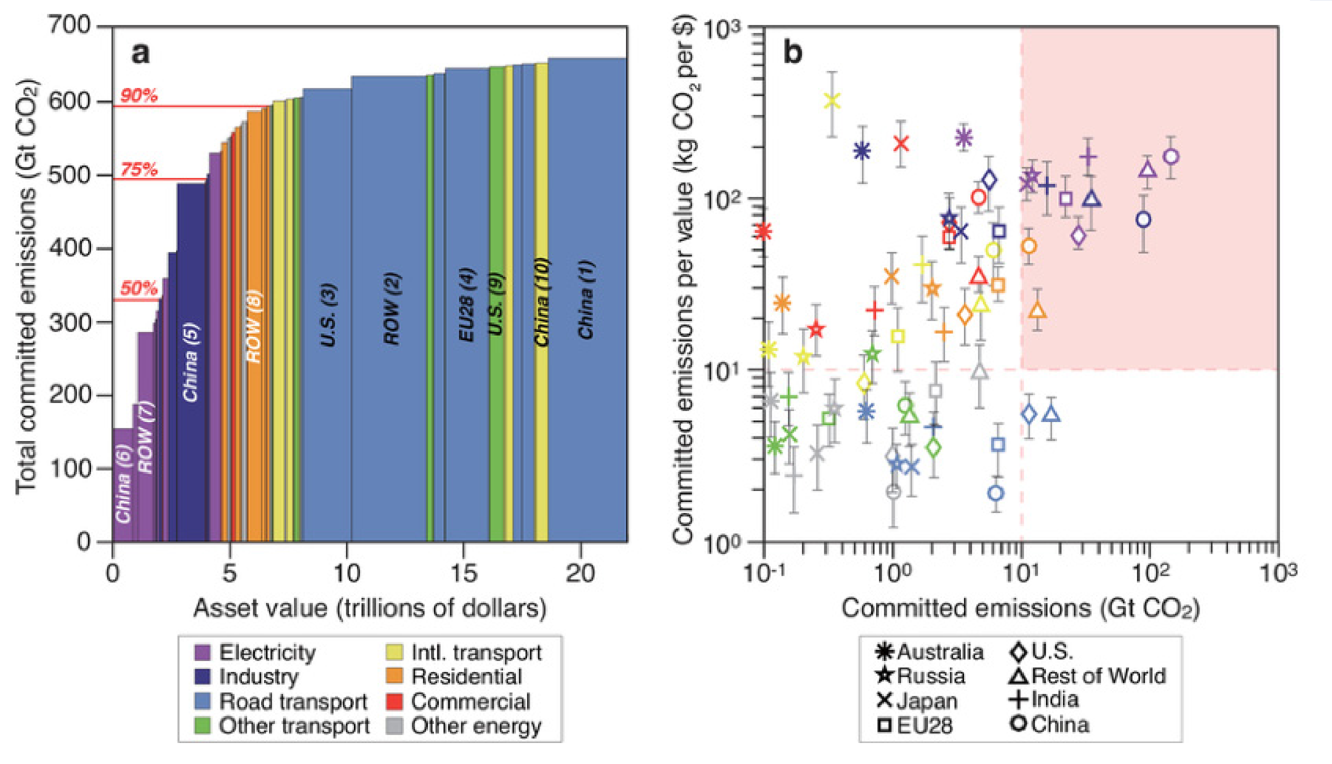


Image credits: courtesy of Dan Tong

Planned lifetime use of $22 trillion worth of 2018 major global infrastructure would emit 658 billion metric tons (Gt) of CO_2[225]—more than the entire 50%–66%-probability 1.5 C° global-warming budget (~420–580 Gt), or perhaps two-thirds of the 2° budget (~1,170–1,500 Gt). Of these assets, the half in road transport will retire three times faster than industrial assets, but could often be advantageously scrapped even sooner, sped by capitalizing avoided fuel costs.

Fossil-fueled power plants (11%) are two-thirds more carbon-intensive per dollar invested than industry and 25–35 times more than transport. Dominated by recently built Chinese plants, they're generally lucrative to retire immediately via efficient instruments like securitization. Meanwhile, dispatch competition shrinks their runtimes, while climate concerns and increasing awareness of the competitive landscape deter construction of planned but prestranded assets. Many overbuilt heavy industrial plants (9%), again chiefly in China and often relatively young, also invite early closure.

Globally, power and industrial assets are the richest target, totaling over 75% of committed emissions but under 25% of asset value. The other assets are mainly ships (starting to be scrapped or retrofitted if inefficient, then fuel-switched, as data transparency reveals each vessel's efficiency to charterers) and buildings (ripe for deep retrofit, coordinated with major building events to make the savings much bigger and cheaper). This prospector's guide reveals vast lodes of cheap decarbonization in troubled assets ripe for rapid displacement by clean and profitable ones.

As often before, we'll learn that many problems look impenetrable until someone cracks them—often by restating the problem correctly, making its solution self-evident. And as with energy and resource efficiency generally, rethinking each desired end-use service as a whole system reveals design opportunities for deeper, cheaper savings of money, emissions, and risk.[226]

For radical energy and materials efficiency, the opportunity portfolio looks so broad, deep, and dynamic that much as Six Sigma revolutionized quality, so we may now aspire to at least Five Eta—engineers' symbol for efficiency—in industrial heat (including materials efficiency) and approaching that in heavy transport and freight logistics. In turn, materials efficiency plus electric end-use efficiency could greatly reduce the next 30 years' conventionally projected 5X rise in total electricity demand,[227,228] speeding a bigger renewable share but needing far lower investments. (Already, the UN's renewable energy agency IRENA found 2.2X electricity growth to 2050 sufficient;[229] the options described here, and others not yet included, could trim it further.) So the prize is immense for entrepreneurs who assemble the intricate jigsaw puzzle of demand-side opportunities.

Perhaps heavy transport and industrial heat look hard to decarbonize because we think they're hard. This article's examples suggest that may be a losing bet. Let's find out. As Henry Ford said, "Whether you think you can, or whether you think you can't, you're right."

Endnotes

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3. Of the archetypical scenarios featured in IPCC's 2018 ***1.5˚C report***, only one requires just natural systems without engineered carbon removal (A. Grübler et al., **A Low Energy Demand Scenario For Meeting The 1.5°C Target And Sustainable Development Goals Without Negative Emission Technologies**). Yet its savings are technically conservative (e.g., it targets 3 L/100 km [78 mpg] new cars in 2050, but the 1.7 L/100 km model I drive [138 mpg on the same German test cycle] began profitable production in 2013) (A. Lovins, "**Reframing Automotive Fuel Efficiency**," Society of Automotive Engineers, SAE J. STEEP 1(1):59–84, 2020, **https://doi.org/10.4271/13-01-01-0004)**.

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5. At the end of 2020, the Chair of the ETC wrote: "We now know that total decarbonisation is technically feasible at very low cost....I will bet that in 12 years' time the current...chair [of the UK Climate Change Committee] will need to explain why the committee's latest estimates are again too pessimistic" (Lord Adair Turner, "The costs of tackling climate change keep on falling," *Financial Times*, 11 Dec 2020). But as this paper shows, we can say that right now.

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39 Opportunity cost minus the nearly-zero renewable production cost, pricing low enough to make viable the newly electrified (directly or via hydrogen) end use that creates the new market for the surplus electricity; thus the clean-energy providers can strongly influence the pace of developing their own new market.

40 This versatile fuel, fertilizer, and reductant could find competitive use in many uses and sectors. Climate Care founder Mike Mason believes it could offer fire-safety and toxicity advantages in aviation if delivered cold and frozen in situ.

41 But less renewable growth than one might suppose, because electric vehicle propulsion and heat pumps are severalfold more efficient than fueled engines and burners, and many industrial processes become more efficient when electrified. Therefore, electrifying all heat and mobility could need very roughly as much electricity again as is now used—if energy productivity remained fixed, but it shouldn't. The United States has about average energy efficiency (in 2005, 14% as efficient as physics permits compared with the 11% global average, but since then, countries like China and India have improved their efficiencies faster). A. Lovins et al., in the RMI business and design book ***Reinventing Fire*** (Chelsea Green, White River Junction VT, 2011), p. 204, showed how the United States in 2010–50, at a historically reasonable pace, could quadruple its electric end-use efficiency at an average cost one-tenth today's average electricity price—using only best 2010 technologies and with limited integrative design. That could more than offset global GDP growth, reducing electricity growth to less than twofold, or conceivably offsetting it via new technologies and integrative design. In the long run, "85% of [global] energy demand could be practically avoided using current knowledge and available technologies" (J. Cullen, J. Allwood, and E. Borgstein, "**Reducing Energy Demand: What Are the Practical Limits?**," *Environmental Science and Technology* 45(4):1171–1718, 2011).

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45 This exceeded the 2X efficiency gain predicted by RMI's report ***Transformational Trucks: Determining the Efficiency Limits of a Class 8 Tractor-Trailer*** without turnpike doubles or several omitted measures, and the 1.82X assumed as a long-term technical potential by the ETC by not including any of those options. Also, heavy trucks in India and many developing countries are **much less efficient** than the assumed US 6.5 mpg (similar to China's) from RMI's report, though duty cycles and payloads differ widely. For comparison, the **Global Fuel Economy Initiative** partners target global new-heavy-truck fuel and CO_2 reductions of 35% in 2005–2035 (corresponding in the US to ~8.8 mpg in 2035) and 70% by 2050 (US ~19 mpge), with electric trucks rising to 19% of 2030 sales and 66% of 2050 sales as the global grid's carbon intensity falls at least 90% in 2020–50.

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75 "Golden Carrots," a type of market transformation program, elicited refrigerator-efficiency leapfrogs in the 1990s in Sweden and the United States, then jumpstarted compact-fluorescent-lamp sales and were used for diverse products (e.g., B. Holloman et al. "**Seven Years Since SERP: Successes and Setbacks in Technology Procurement**," 2002). Just bulk purchasing can transform markets, like Energy Efficiency Services Ltd's brilliant program that bulk-bought and resold 1.5 billion LED lamps, dropping their price 87% and flipping India's lighting market in five years. Now EESL is moving into electric vehicles. PG&E in 2015 proposed reviving and extending Golden Carrot competitions. Bulk buys can also be coupled with ratcheting efficiency standards like Japan's Top Runner program for appliances, or bid outright as described specifically to elicit and derisk radical innovation. For the contest or prize element, see McKinsey & Company, **And the Winner Is…**, 2009.

76 H. Geller & S. Nadel, "Market Transformation Strategies to Promote End-Use Efficiency," *Annual Review of Energy and the Environment* 19:301–346, 1994, **https://www.aceee.org/sites/default/files/publications/researchreports/e941.pdf**; **https://neep.org/tags/market-transformation;** **https://www.imt.org/about/**; **https://www.synapse-energy.com/sites/default/files/Utility-Investment-Market-Transformation-17-057.pdf**.

77 For the general reasons of efficiency, substitution, and circularity summarized by A. Lovins, "**Clean energy and rare earths: Why not to worry**," *Bulletin of the Atomic Scientists*, 23 May 2017, now echoed by similar developments with cobalt. Circularity is rapidly advancing (e.g., **Tim Higgins' article in the Wall Street Journal**), and will scale as enough batteries are scrapped to justify major recycling investment and create steady-state circular materials flows. IEA's May 2021 critical-materials study (**https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions**) unfortunately adopts nominal average materials intensities rather than parameterizing by tractive load, which can vary 2–3-fold for autos and substantially for trucks. For example, RMI's 1996 two-volume study *Hypercars: Materials, Manufacturing, and Policy Implications* included a 115-line-item mass budget for a typical advanced-composite car (hybrid-electric with NiMH batteries, because cheap lithium-ion batteries weren't yet available or expected). The vehicle needed just 21.5 kg of copper, 12.6% more than the average 1994 US production car's 19.1 kg, rather than roughly 110–190% more as IEA assumes by apparently electrifying a heavy, high-drag, steel-dominated car. IEA's headline of roughly 6-fold greater EV use of [critical]

"minerals" is almost all for batteries, whose capacity for a given range can fall 2–3-fold with advantageously improved vehicle efficiency (Lovins, "Reframing Automotive Fuel Efficiency," Society of Automotive Engineers, 2020), more with better batteries, and leverage cobalt/kWh 30X from smartphones to cars.

78 Via electric-bus sales of 37% in 2030 and 93% in 2050, while fueled buses get 2%/y more efficient (*Prospects for Fuel Efficiency, Electrification and Fleet Decarbonisation*, Global Fuel Economy Initiative, 2019).

79 E.g. **https://www.proterra.com/financing-ev-fleets-with-proterra-battery-leasing-program/** and **https://www.highlandet.com/how-we-do-it/**.

80 Siemens, "Siemens Energy and Siemens Mobility jointly drive development of hydrogen mobility," 5 Oct 2020, **https://press.siemens.com/global/en/pressrelease/siemens-energy-and-siemens-mobility-jointly-drive-development-hydrogen-mobility**.

81 **https://www.itdp.org/library/standards-and-guides/the-bus-rapid-transit-standard/what-is-brt/**; and **https://www.cybertran.com**.

82 D. Lee *et al*., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," *Atmospheric Environment* AE 117834, 2020, **https://doi.org/10.1016/j.atmosenv.2020.117834**.

83 S. Gössling and A. Humpe, "The global scale, distribution and growth of aviation: Implications for climate change," *Global Environmental Change* 65:102194, 2020, **https://doi.org/10.1016/j.gloenvcha.2020.102194**.

84 D. Bushnell, "Digital reality vs physical travel," *Professional Pilot*, Oct 2020, **https://www.propilotmag.com/viewpoints/**; "Demo: The magic of AI neural TTS and holograms at Microsoft Inspire 2019," 17 Jul 2019, **https://www.youtube.com/watch?v=auJJrHgG9Mc&feature=emb_logo**.

85 P. Hollinger, "How the promise of electric power could transform aviation," *Financial Times*, 12 Sep 2020, **https://www.ft.com/content/0a58d62e-aeb9-11e8-8d14-6f049d06439c**.

86 McKinsey and Company's 2020 study with the Airbus ecosystem, *Hydrogen-powered aviation: Preparing for take-off*, foresees quicker adoption (starting in 8–13 y) but at higher costs than careful Boeing analyses found nearly two decades earlier (e.g., D. Daggett, "Commercial Airplanes—Hydrogen Fueled Airplanes," presentation to Hydrogen Production and NW Transportation, Pacific Northwest Laboratories, 16 Jun 2003).

87 BP's heavily revised 2020 forecast drops this longstanding assumption.

88 BP Energy Outlook, Feb 2019, "Demand and supply growth by product, 2017–2040" chart, **https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/demand-by-fuel/oil.html**.

89 A. Lovins *et al*., *Winning the Oil Endgame*, RMI, 2004, *State of the Art* projection, and its Technical Annex 12.

90 A. Lovins and RMI, *Reinventing Fire*, Chelsea Green, 2011, pp. 56–57; A. Lovins, "The aviation efficiency revolution," Keynote Presentation at Air Transport Action Group's Global Sustainable Aviation Forum, 13 May 2019, **https://rmi.org/insight/aviation-efficiency-revolution/**.

91 *Commercial Aircraft Propulsion and Energy Systems Research*, National Academy of Sciences, 2016, **https://doi.org/10.17226/23490**; J. Felder, "NASA N3-X with Turboelectric Distributed Propulsion," NASA, 2015, **https://ntrs.nasa.gov/search.jsp?R=20150002081 2019-02-10T18:41:39+00:00Z**.

92 Veitch, L., "Assessment of the DARPA Affordable Polymer Matrix Composites Program," Institute for Defense Analyses D-2068, 1997, II-4 and III-3, **https://apps.dtic.mil/sti/pdfs/ADA332907.pdf**.

93 N. Cramer et al., *Smart Materials and Structures* 28:055006, 1 Apr 2019, **https://doi.org/10.1088/1361-665X/ab0ea2** (**https://cba.mit.edu/docs/papers/19.03.MADCAT.pdf**). Images from **https://mit.edu/archive/spotlight/shape-changing-plane-wing/**.

94 Such as long thin truss- or strut-braced wings, aerodynamic and engine improvements, ultralight composite structures, hybrid propulsion (gas-turbine-assisted takeoff and range reserve plus electric cruise), podded or buried propulsors ingesting air from the boundary layer, and optionally, blended-wing-body forms instead of tube-and-wing, plus other options, all artfully combined.

95 *Celera 500L*, Otto Aviation, **https://www.ottoaviation.com/celera-500l**; "Otto Aviation Completes 31 Successful Test Flights with Its Groundbreaking Celera 500L," 26 Aug 2020, **https://static1.squarespace.com/static/5f3541f19bb2e80bcd4b0f98/t/5f4fec8abb6d0e29e6cac867/1599073419663/SZ_Otto+Aviation+Celera+500L+Announcement+press+release_August+2020_Rev-A.pdf**

96 N. Cramer, *et al.*, "Elastic shape morphing of ultralight structures by programmable assembly," *Smart Materials and Structures* 28.5: 055006, 2019.

97 RMI's work with shipping, cruise-ship, Naval surface combatant, and yacht design does not support the conventional view that conventionally planned efficiency gains come anywhere near exhausting cost-effective opportunities.

98 N. Bullard, "In the Race for Investment Dollars, Cars Are Pulling Ahead," Bloomberg New Energy Finance, 28 Jan 2021.

99 "Swedish Collaboration Unveils World's Largest Sail Powered Car Carrier," *The Maritime Executive*, 11 Sep 2020, **https://www.maritime-executive.com/article/swedish-collaboration-unveils-world-s-largest-sail-powered-car-carrier**; H. Mason, "Modernizing the mechanical rotor sail," *Composites World*, 23 Nov 2020, **https://www.compositesworld.com/articles/modernizing-the-mechanical-rotor-sail-**; N. Degnarain, "A New Golden Age of Sailing Is Here: Where Is The Leadership?," 1 Dec 2020, *Forbes*, **https://www.forbes.com/sites/nishandegnarain/2020/12/01/a-new-golden-age-of-sailing-is-here-where-is-the-leadership/**.

100 "Maersk will operate the world's first carbon neutral liner vessel by 2023—seven years ahead of schedule," A.P. Møller-Maersk, 21 Feb 2021, **https://www.maersk.com/news/articles/2021/02/17/maersk-first-carbon-neutral-liner-vessel-by-2023**; **www.zerocarbonshipping.com**; J. Calma, "Retail giants look to greener cargo ships to meet climate goals," *The Verge*, 16 Mar 2021, **https://www.theverge.com/2021/3/16/22334173/retail-cargo-ships-climate-change-goals-maersk**.

101 The Danish, then Global, Maritime Forum, led by 34 maritime CEOs, persuaded the International Maritime Organization to target a 50% intensity cut by 2050 with mandatory emissions reporting guidelines. Building on that groundwork, the Poseidon Principles got banks holding a fourth of shipping debt to commit to Paris climate alignment. The Getting to Zero coalition turned ambition into action by bringing together industry, customers, and financiers. Momentum built as Maersk targeted net-zero emissions by 2050. Now the once-stodgy shipping sector is helping lead heavy transport off carbon. For aviation, IATA's roadmap targets carbon-neutral growth from 2020, halving 2005 net aviation CO_2 emissions by 2050. Some players will move much faster and further, encouraging the others.

102 RMI, **https://rmi.org/our-work/industry-and-transportation/material-value-chains/comet/**.

103 RMI's collaboration with the US General Services Administration, the nation's largest commercial landlord, has also catalyzed GSA's archetypical leadership on reducing materials

intensity and materials' embodied energy ("**Policy Recommendations for Procurement of Low Embodied Energy and Carbon Materials by Federal Agencies**," GSA, 17 Feb 2021).

104 A. and L. Lovins and P. Hawken, *Natural Capitalism*, Little Brown, 1999, analyzed from I. Wernick and J. Ausubel, "National Materials Flows and the Environment," *Annual Review of Energy and the Environment* 20:463–492 (1995). A global update found 2010 per-capita in-use stocks of 47 tonnes of concrete, 3.8 of iron and steel, 0.4 of plastics, and 0.1 of aluminum: F. Krausmann et al., "Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use," *Proc. Nat. Acad. Scis.* 114(8):1880–1885, 2017, **https://doi.org/10./1073/pnas.1613773114**.

105 This number depends substantially on choice of system boundary, and whether non-CO_2 gases are counted.

106 E. Worrell, J. Allwood, and T. Gutowski, "The Role of Material Efficiency in Environmental Stewardship," *Annual Review of Environment and Resources* 4:575–598, 2016, **https://doi.org/10.1146/annurev-environ-110615-085737**.

107 Z. Cao *et al.*, "The sponge effect and carbon emission mitigation potentials of the global cement cycle," *Nature Communications* 11:3777, 2020, **https://doi.org/10.1038/s41467-020-17583-w**.

108 M. Liebreich, "Peak Emissions Are Closer Than You Think," Bloomberg New Energy Finance, 17 Dec 2019.

109 For example, friction-minimizing pipe and duct design, if fully applied, could save global pump and fan energy equivalent to about a fifth of the world's electricity. Yet that's not in any standard engineering textbook, industry forecast, government study, or climate model, because it's cross-cutting, not sector-specific, and about design, not technology (A. Lovins, "**How big is the energy efficiency resource?**," *Environmental Research Letters* 13:090401, 2018). Efficient pump/pipe and fan/duct systems raise the one-fifth potential to about one-third by unlocking the economics of a 35-measure motor-system retrofit package that can save twice as much electricity, at a fifth the unit cost, commonly saved by the usual two measures (A. Fickett, C. Gellings, and A. Lovins, "Efficient Use of Electricity," *Scientific American*, Sep 1990, 65–70; A. Lovins *et al.*, *The State of the Art: Drivepower,* RMI, 1989). Few if any major materials makers yet capture such opportunities.

110 Renewable direct heat was 4.2% of 2017 total final energy consumption or ~16 EJ/y, derived ~89% from nontraditional biomass, 9% solar, and 2% geothermal, according to IEA data in A. Lovins *et al.*, "**Recalibrating Climate Prospects**," *Environmental Research Letters* 14:120201, Dec 2019. About 49% of the world's final energy consumption in 2008 was delivered as heat (J. Cullen and J. Allwood, "The Efficient Use of Energy," *Energy Policy* 38(1):75–81, 2010).

111 The first offshore-wind-to-hydrogen project is due to start up in 2021, with 17 GW in the pipeline and a 2030 EU goal of 40 GW (Y. Zhou, "**Hydrogen from Offshore Wind: A Primer**," BNEF, 29 Mar 2021).

112 M. Tengler, T. Brandily, X. Wang, "1H 2021 Hydrogen Levelized Cost Update: Costs of renewable H2 to fall faster than expected," 7 Apr 2021, **https://www.bnef.com/insights/26011/view** (subscriber website), summarized by D. Iaconangelo, "Hydrogen with CCS faces same fate as coal—report," 8 Apr 2021, **https://www.eenews.net/energywire/2021/04/08/stories/1063729469**.

113 S. Kraemer, "CEMEX and Synhelion to Demo Zero CO_2 Cement," 20 Nov 2020, **https://www.solarpaces.org/cemex-and-synhelion-to-demo-zero-co2-cement/**.

114 A. Lovins, "Energy strategy: the road not taken?," *Foreign Affairs* 55(1):65–96 (Oct 1976). The phrase is from architect Prof. Doug Kelbaugh FAIA.

115 A. Lovins and K. Bond, "Can a virus and viral ideas speed the world's journey beyond fossil fuels?," *Environmental Research Letters*, 2021.

116 This refers to shipping, aviation, and cement. For decarbonizing process heat, assuming 2¢/kWh renewable electricity and ETC's *Mission Possible*'s materials circularities and efficiencies, ~64% of abatement cost is for cement and ~10% for steel. After the shipping and aviation improvements described above, decarbonizing cement would be the largest single cost in the "harder-to-abate" sectors.

117 J. Rissman *et al.*, "Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070," *Applied Energy* 268:114848, 2020. Cf. note 77 for important omissions. Complementarity with materials efficiency is surveyed in J. Allwood et al., "Material efficiency: A white paper," *Resources, Conservation and Recycling* 55:362–381, 2011, **https://doi.org/10.1016/j.resconrec.2010.11.002**, and E. Worrell and J. Carreon, "Energy demand for material in an international context," *Philosophical Transactions of the Royal Society* A 375:20160377, 2016, **https://doi.org/10.1098/rsta.2016/0377**.

118 C. Voigt, "Synthetic biology 2020–2030: six commercially-available products that are changing our world," *Nature Communications* 11:6379, 2020, **https://doi.org/10.1038/s41467-020-20122-2**.

119 Such as single-atom catalysis by iron, cobalt, and nickel in O_2 and CO_2 reduction and H_2 evolution (S. Mitchell and J. Pérez-Ramírez, "**Single atom catalysis: a decade of stunning progress and the promise for a bright future**," *Nature Communications* 11:4302, 2020).

120 In principle, the chemical industry is exothermic—its reactions release enough heat to drive them—but in practice, bulk chemical production often uses century-old processes. Chemicals other than ammonia and thermoplastics use enormously diverse processes—130 main ones for just the 18 largest products. IEA's 2013 **Technology Roadmap** says 1.6–1.8 $GtCO_2$/y could be saved by efficiency gains to 2050, and 0.35 by process intensification, cogeneration, recycling, and energy recovery.

121 P. Levi and J. Cullen, "Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products," *Environmental Science & Technology* 52:17251734, 2018.

122 For example, an authoritative 2018 review of "net-zero emissions energy systems" mentions reduced materials intensity only in one passing sentence before concluding that decarbonization needs process breakthroughs or carbon capture and sequestration (S.J. Davis *et al.*, "Net-zero emissions energy systems," *Science* 360[6396]:eaas9793 [29 Jun 2018], **https://doi.org/10.1126/science.aas9793)**.

123 "Industrial Transformation 2050," Material Economics, 2019, University of Cambridge Institute for Sustainability Leadership, **https://materialeconomics.com/latest-updates/industrial-transformation-2050**.

124 These are high-end estimates from Materials Economics analysis for the ETC's *Mission Possible* report, which cites the EU-centric analysis **The Circular Economy—a Powerful Force for Climate Mitigation**, 2018. Advanced recycling techniques that sort by material and grade are rapidly improving.

125 W. Mathis, "Green Ammonia for Fertilizer Planned by Giant Wind Farm Builder," 5 Oct 2020, **https://www.bloomberg.com/news/articles/2020-10-05/orsted-aims-to-make-green-ammonia-for-fertilizer-with-wind**.

126 Even without shifting basic farming practices, the EU, where 40% of fertilizer is already organic, could save 45% of ammonia by 2050 (12% from reduced food waste, 24% from more precise and efficient ammonia application, and 8% by greater use of available organic fertilizer), with major co-benefits. Of this potential, 40%–75% is assumed to be realized (*Industrial Transformation*

2050—Pathways to Net-Zero Emissions from EU Heavy Industry, Material Economics, 2019, **https://materialeconomics.com/latest-updates/industrial-transformation-2050)**.

127 K. Bond, "The Future's Not in Plastics," 4 Sep 2020, **https://carbontracker.org/reports/the-futures-not-in-plastics/**; Pew Charitable Trusts, "Breaking the Plastic Wave," 2020, **https://www.pewtrusts.org/-/media/assets/2020/07/breakingtheplasticwave_report.pdf**. See also Lovins, *Natural Capitalism*, 1999, pp. 170–212.

128 B. D'Amico, P. Pomponi, and J. Hart, "Global potential for material substitution in building construction: The case of cross laminated timber," *Journal of Cleaner Production* 279:123487, 2021, **https://doi.org/10.1016/j.jclepro.2020.123487**.

129 *The Circular Economy—a Powerful Force for Climate Mitigation*, Material Economics, 2018, **https://materialeconomics.com/publications/the-circular-economy**, p. 20, apparently referring to EU data, and totaling 85% of embodied CO_2 from these two uses (p. 21).

130 International Energy Agency, *Material efficiency in clean energy transitions*, Mar 2019, **https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions**.

131 *Ibid.*, pp. 40–45, elaborated in the study's later value-chain analyses; practical savings from graph on p. 63.

132 Particularly in China, which makes nearly half the world's steel. The Environment Minister personally led a recent raid on polluting mills, and the central government is cracking down with tighter production curbs ("**China's Green Campaign Leaves Metals Braced for More Ructions**," *Bloomberg News*, Mar 2021).

133 S. Matthis, "Fossilfrit stål kan börja levereras redan i år," *Industrinyheter*, 8 Mar 2021, **https://www.industrinyheter.se/20210308/31353/fossilfrit-stal-kan-morja-levereras-redan-i-ar**.

134 Colocation relieves railway bottlenecks and can be equivalent to a 20%-lower iron-ore price. Photolytic hydrogen, needing no electricity, also shows promise, and another competitor, Boston Metal's molten-oxide electrolysis, directly reduces iron oxide as if it were alumina, reportedly using 15%–30% less electricity per steel ton than green-hydrogen direct reduction, and scaling down much better for flexible siting.

135 T. Koch-Blank, "Green Steel: A Multi-Billion Dollar Opportunity," RMI, 29 Sep 2020, **https://www.rmi.org/green-steel-a-multi-billion-dollar-opportunity/**.

136 *Mission Possible*, ETC; R. Dell, "Build Clean: Industrial Policy for Climate and Justice," ClimateWorks Industry, Dec 2020.

137 R. Milford *et al.*, "The Roles of Energy and Material Efficiency in Meeting Steel Industry CO_2 Targets," *Environmental Science & Technology* 47(7):3455-3452, 2013, **https://doi.org/10.1021/es3031424**.

138 M. Moynihan and J. Allwood, "The flow of steel into the construction sector," *Resources, Conservation and Recycling* 68:88–95, 2012, **https://doi.org/10.1016/j.resconrec.2012.08.009**; D. Cooper and J. Allwood, "Reusing steel and aluminium components at end of product life," *Environmental Science & Technology* 46(18):10334–10340, 2012, **https://doi.org/10.1021/es301093a**; 2012 and 2008 data respectively.

139 R. Milford *et al.*, "Supporting Information: The last blast furnace?," 11 Dec 2012, U. of Cambridge, p. 24; M. Moynihan and J. Allwood, "Utilization of structural steel in buildings," *Proceedings of the Royal Society A* 470(2168):20140170, 2014.

140 Broadly consistent with Material Economics, *Industrial Transformation 2050*, 2019, which says construction often uses 35%–45% more steel and 67%–100% more cement than necessary. *The Circular Economy*, p. 6, refers to "the near 100% overuse of steel in buildings relatively

to what is strictly required to meet design specifications," and on p. 150, confirms common ~2X overspecification. A limited subset of design improvements could save 20% of UK concrete (W. Shanks, C. Dunant, M. Drewnlok, R. Lupton, A. Serrenho, and J. Allwood, "How much cement can we do without? Lessons from cement material flows in the UK," *Resources, Conservation and Recycling* 141:441–454, 2019), whose Figure 3 provides perhaps the first flowchart of what structural forms and functions use how much cement. Increasing buildings' lifetime is another obvious opportunity (*The Circular Economy*, p. 152).

141 Foundry, additive-manufacturing, and other fabrication innovations can also use far less steel more efficiently and in advantageous new ways.

142 P. Horton and J. Allwood, "Yield improvement opportunities for manufacturing automotive sheet steel components," *Journal of Materials Processing Technology* 249:78–88, 2017.

143 Gasifying or pyrolyzing auto shredder residue is also becoming competitive with incineration and landfilling, increasing recovery opportunities to make new plastics (I. Savut, "**Green Options for Recycling Old Cars Are Competing on Cost**," BNEF, March 2021).

144 R. Modaresi *et al.*, "Global Carbon Benefits of Material Substitution in Passenger Cars until 2050 and the Impact on the Steel and Aluminum Industries," *Environmental Science & Technology* 48:10776–10784, 2014.

145 To be sure, 49% of automakers surveyed by WardsAuto in 2014 cited lightweighting as their main strategy for meeting US 2017–25 efficiency standards (vs. engine efficiency 59% and electrification 26%) (D. Winter, "**Automakers focus on lightweighting to meet CAFÉ standards**," *WardsAuto*, 6 Aug 2014). The lightweighting focus rose to **63% in 2016**, and remained tops in **2017** and **2018**. Sponsorship shifted around 2019 from DuPont to the American Iron and Steel Institute, and the story changed, but the 2019 survey found 44% of respondents saying vehicle materials and architectures will be "**totally different**" in 10 y than today.

146 Lovins, "Reframing Automotive Fuel Efficiency," Society of Automotive Engineers, 2020.

147 Renormalizing from original 1994 base vehicle to 2017 US average auto (Avauto), based on detailed Bill of Materials from A. Lovins et al., *Hypercars: Materials, Manufacturing, and Policy Implications*, vol. 1, RMI, 1996, using the 2000 SUV virtual design in A. Lovins and D. Cramer, "**Hypercars, hydrogen, and the automotive transition**," *International Journal of Vehicle Design* 35(1/2):50–85, 2004. The 25%-heavier 2017 Avauto assumed here weighs 650 kg, or 64% lighter than with US average 2017 composition. Its ferrous content would fall from almost 1,800 to ~100 kg while its polymer content rose ~82% from ~155 to ~280 kg, or from 9% to 44% of curb mass. For comparison, the lightest carbon-fiber concept car shown by a major automaker—Toyota's 2007 1/X, with the interior volume of a Prius but half the fuel use and one-third the weight—weighed 420 kg with a plug-in hybrid powertrain and would have weighed 400 kg with a standard Prius hybrid powertrain, for a 70% weight saving. EU automaking's 2013 steel scrap rate was ~43%—~7X the scrap rate for a modern carbon-fiber structural auto parts-making process like Dieffenbacher's Fiberforge, whose prepreg carbon-tape scrap can all be valuably reused.

148 Such as the 30% primary-steel savings for mobility services stated (or 23% graphed) in **The Circular Economy—a Powerful Force for Climate Mitigation**. For comparison, China's flagship autos are planned to lose ~79% of their iron and steel in 2020–30 while each adds an average of 49 kg of carbon fiber—about enough for a composite body-in-black (A. Restauro and J. Attwood, "**Auto Lightweighting Scenarios in the U.S., EU and China**," Bloomberg NEF, 21 Oct 2019).

149 Including scrapping steel autos sooner to help rebalance global recycling, reducing recycling's

copper-contamination constraints (which the shift to electric vehicles and skateboard architectures should facilitate), and avoiding all ~43% of automotive stamped sheet-steel now scrapped (I. Flint *et al.*, "Material Flow Analysis with Multiple Material Characteristics to Assess the Potential for Flat Steel Prompt Scrap Prevention and Diversion without Remelting," *Environmental Science & Technology* 54:2459–2466, 2020).

150 *The Circular Economy* shows lightweighting cars as the costliest EU circular-economy option, at ~€90/tCO_2. Yet I explain in "Reframing Automotive Fuel Efficiency" why carbon-fiber auto bodies are paid for by smaller powertrain, mass decompounding, and simpler automaking. Unfortunately, the basis of the second-highest cost, for materials efficiency in buildings, is also opaque.

151 *Material efficiency in clean energy transitions*, IEA, Mar 2019, p. 77. The 40% "practical limits" on lightweighting by 2060 are on p. 130; cf. Exhibit 6d's 70% in 2007. The saving is read from the graph on p. 74.

152 *The Circular Economy*, Material Economics, 2018, pp. 116–139.

153 It may also become attractive to build battery functionality into composite structural components (L. Asp et al., "**A Structural Battery and its Multifunctional Performance**," *Advanced Energy and Sustainability Research* 2021(2):2000093, 2021).

154 A. Lovins, "Reframing Automotive Fuel Efficiency," Society of Automotive Engineers, 2020.

155 A. Lovins and D. Cramer, "Hypercars, hydrogen, and the automotive transition," *International Journal of Vehicle Design*, 2004, **https://doi.org/10.1504/IJVD.2004.004364**.

156 **Aptera.co** and **Lightyear.one**. The author advises both firms.

157 M. Yang, "China's aluminium production surged by 5% in 2020, producing more emissions than Indonesia," 7 Feb 2021, **https://ember-climate.org/commentary/2021/02/07/china-aluminium-2020-emissions/**.

158 Rusal supports this move (S. Birns, "**'Green' aluminum gains momentum**," *MetalMiner*, 21 Jan 2021).

159 "LME Issues Discussion Paper on Sustainability Plans," Aug 2020, **https://www.lme.com/en-GB/News/Press-room/Press-releases/Press-releases/2020/8/LME-issues-discussion-paper-on-sustainability-plans**.

160 Electric vehicles could also halve the need for castings that now make downcycling work (*The Circular Economy*, pp. 106–109).

161 *The Circular Economy*, p. 102.

162 J. Cullen and J. Allwood, "Mapping the Global Flow of Aluminum: From Liquid Aluminum to End-Use Goods," *Environmental Science & Technology* 47(7):3057–3064, 2013.

163 This process absorbed ~0.9 GtCO_2 in 2013, and during 1930–2013, ~16.5 GtCO_2, or 43% of the CO_2 process emissions from making cement during the same period, excluding releases from fossil-fuel combustion (F. Xi *et al.*, "Substantial global carbon uptake by cement carbonation," *Nature Geoscience* 9:880–883, 2016).

164 This traditional binder is ~7%–20% of concrete but emits at least 95% of its CO_2 ("**Industrial Transformation 2050**," Material Economics, 2019—an excellent tutorial on the surprising scope for saving cement and concrete). Three pathways are sketched at p. 181, of which demand-side ones valuably buy time, defer or avoid investment and cost, yet aren't in most roadmaps (p. 183).

165 D. Perilli, "The race to zero," *Global Cement*, 23 Sep 2020, **https://www.globalcement.com/news/item/11384-the-race-to-zero**, and for a

terse summary of 15 methods, "A short look at low carbon cement and concrete," 1 Apr 2020, *id.*, **https://www.globalcement.com/news/item/10667-a-short-look-at-low-carbon-cement-and-concrete**.

166 "Industrial Transformation 2050," Material Economics, 2019, p. 173. Hoffmann Green Cement Technologies is building in France a second plant to make clinker-free cement from blast-furnace slag, clay, and gypsum (D. Perilli, **Global Cement**, 20 Jan 2021).

167 *Industrial Transformation 2050,* Material Economics, 2019, p. 173, **https://materialeconomics.com/latest-updates/industrial-transformation-2050**.

168 *Mission Possible*, ETC, p. 152.

169 G. Habart, S. Miller, V. John, J. Provis, A. Favier, A. Horvath, and K. Scrivener, "Environmental impacts and decarbonization strategies in the cement and concrete industries," *Nature Reviews: Earth and Environment* 1:559–573, 2020, **https://doi.org/Profita**—an authoritative and admirable, if supply-centric, primer.

170 J. Lehne and F. Preston, "Making Concrete Change: Innovation in Low-carbon Cement and Concrete," Chatham House, 13 June 2018, **https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete**.

171 V. Atakan estimates the current swing from net emissions to net absorption could be ~3–5 GtCO$_2$/y if only Solidia cement and carboxylates were used (personal communication, 15 Feb 2021).

172 V. Atakan, N. DeCristofaro, and W. Joy, Comment on C. Hepburn et al., "The technological and economic prospects for CO$_2$ utilization and removal," *Nature* 575:87–97, 2019, **https://www.nature.com/articles/s41586-019-1681-6**.

173 Such as bioMASON (**www.biomason.com**) for precast cement tiles.

174 E. Thomson, "Cleaning Up Steel," The Engine, 3 Dec 2019, **https://the-engine.medium.com/cleaning-up-steel-72f4d0ea8f0d**, provides a useful lay summary.

175 Y. Qiao, "Ultralow-Binder-Content Composite and Its Applications," 3 Oct 2018 UCSD seminar, **https://cer.ucsd.edu/_news-events-articles/2018/Yu-seminar.html**; "Extremely Durable and Low-Cost Concrete: Ultralow Binder Content and Ultrahigh Tensile Ductility," 14 Nov 2020, **https://www.arpa-e.energy.gov/sites/default/files/2020-11/14%20UCSD%20-%20Yu%20Qiao.pdf**; K. Oh *et al.*, "Compaction self-assembly of a low-binder-content geopolymer material," *Journal of Materials Science* 55(32), Nov 2020, **https://doi.org/10.1007/s10853-020-05069-5**; lay summary by J. Stein, "New Innovation Drives Down Carbon Dioxide Emissions from Cement," 20 Aug 2019, **https://energycentral.com/c/ec/new-innovation-drives-down-carbon-dioxide-emissions-cement**.

176 T. Ibell, J. Norman, and O. Broadbent, "Nothing is better than something," *The Structural Engineer*, p. 12, Jun 2020, **https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-6/nothing-is-better-than-something/**, and "How can we create an engineering industry while building nothing?," *The Structural Engineer*, Jul 2020, **https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-7/how-can-we-create-an-engineering-industry/**, aptly evolve the design task from build efficiently to build clever to build less or build nothing.

177 Including by reducing the ~10%–20% on-site waste of construction materials. *The Circular Economy*, p. 150. Exh. 6.8 at p. 157 adopts practical mass savings of 4% from lower on-site waste, 9% from component reuse, and just 10% from more-efficient use of building materials, chiefly steel and cement where higher-quality, better-specified materials save 20%–30%. Habart, *et al.*, "Environmental impacts and decarbonization strategies," *Nature Reviews*, 2020, also cites a 2018 EC finding of ~50% cement savings by better specifying exposure class.

178 *Mission Possible* and many other assessments note the opportunity to make buildings last much longer. W. Zhu, W. Feng, X. Li, and Z. Zhang, "Analysis of the embodied carbon dioxide in the building sector: A case of China," *J. Cleaner Production* 269:122438, 2020, say typical Chinese building life is only ~30 years. J. Rissman, "**Cement's Role in a Carbon-Neutral Future**," 20 Jan 2021, notes that with proper maintenance, concrete structures can last for centuries; the Pantheon dome, made of 4,500 tons of unreinforced concrete, was built in 126 CE and remains the world's largest such structure today. Of course, deep energy retrofits of existing buildings both preserve embodied energy and greatly reduce or eliminate net operating energy.

179 Demolished concrete contains ~30%–40% recoverable unhydrated cement: **SmartCrusher BV** claims ~2.5 $GTCO_2$/y, and *The Circular Economy*, p. 142, explains why indirect benefits from recovering 30%–40% unhydrated cement can raise CO_2 savings to nearly 50%. That's presumably why *Mission Possible*, p. 105, Exh. 505 shows 17% achievable CO_2 savings by 2050 from recycling cement in demolished EU buildings. LafargeHolcim's Susteno cement, sold in Switzerland, includes 20% processed fine mixed granulate from demolished buildings, while its EcoPact, like HeidelbergCement's EcoCrete, reuses coarse concrete demolition waste as aggregate. "Environmental impacts and decarbonization strategies in the cement and concrete industries," *Nature Reviews* also says about a tenth of concrete use may be saveable by reusing intact concrete elements in new construction.

180 "Industrial Transformation 2050," Material Economics, 2019, p. 157 and p. 166.

181 Potable water, sanitation, stormwater management, electricity, fuel (if also needed), and telecommunications. On-site solutions for all six could eliminate the need to lay pipes and wires in trenches all over the building site.

182 *Reevaluating Stormwater: The Nine Mile Run Model for Restorative Development*, Rocky Mountain Institute, 1999, **https://rmi.org/insight/reevaluating-stormwater-the-nine-mile-run-model-for-restorative-development/**; and pilot projects by Tree People, *Natural Capitalism*, pp. 226–227.

183 J. Womack and D. Jones, *Lean Solutions*, Simon & Schuster Free Press, 2005; *Natural Capitalism*, Ch. 7; *Mission Possible*, ETC, 2018, p. 147.

184 Analogous "performance-based design fees" can greatly improve energy efficiency and benefit the best designers (Eley Associates, "**Energy Performance Contracting for New Buildings**," 2004).

185 G. Habart, et al., "Environmental impacts and decarbonization strategies," *Nature Reviews: Earth and Environment* 1:559–573, 2020.

186 J. Orr, M. Drewniok, I. Walker, T. Ibell, A. Copping, and S. Emmitt, "Minimising energy in construction: Practitioners' views on material efficiency," *Resources, Conservation and Recycling* 140:125–136, 2019, **https://doi.org/10.1016/j.resconrec.2018.09.015**, **https://purehost.bath.ac.uk/ws/portalfiles/portal/186484616/MEICON_Survey_Paper_clean.pdf**.

187 *Material efficiency in clean energy transitions*, IEA, 2019, pp. 123–127.

188 J. Schlaich and R. Bergermann, *Leicht Weit / Light Structures*, Prestel Verlag, 2005.

189 Stimulating examples, including using ice formwork, are in the April 2019 Special Issue of *Structures* 18, "**Advanced Manufacturing and Materials for Innovative Structural Design**." A useful 2011 history is at **Fabwiki**.

190 Mark West, *The Fabric Formwork Book*, Routledge, 2016; CAST (Centre for Architectural Structures and Technology), University of Manitoba, Winnipeg (**http://umanitoba.ca/cast_building/**); W. Hawkins *et al.*, "Flexible formwork technologies—a state of the art review," *Structural Concrete* 17.10.1002, 2016, **https://doi.org/10.1002/suco.201600117;**

K. Kostova, T. Ibell, A. Darby, and M. Evernden, Form-finding approach for flexibly formed concrete elements," *Engineering and Computational Mechanics* 172(3):96–105, 2019, **https://doi.org/10.1680/jencm.19.00005**.

191 For an 8.5 meter span, thinning the slab from 30 cm to 4 cm, folded in trapezoidal corrugations 26 cm high overall and mass-equivalent to a 6-cm flat slab, and reinforced not with steel rebar but with a prestressed €20/kg carbon-fiber grid. Using €150/m^3 concrete, the total cost of a 5x1.2m floorplate is €43.5/m^2, or for a 10-meter span, €52/m^2, both attractively low (personal communications, Schlaich Bergermann Partner [Berlin], 14 Oct 2020). The prestressed carbon-fiber rovings are 4X lighter than steel, 5X stronger (tensile), and >35% cheaper, and make reinforced-concrete structures typically 50%–80% lighter and 50%–70% less CO_2-intensive ("**Prestressed Textile Concrete**," Ginkgo Textilbeton).

192 For buildings with identical square plans, using a standard concrete shear wall structure; using a moment-resisting frame design, these ratios are 29% and 47%. A survey of five Melbourne office buildings (a small sample) found ~60% more embodied structural energy in high- than low-rise buildings (G. Treloar, R. Fay, B. Ilozor, and P. Love, "An analysis of the embodied energy of office buildings by height," *Facilities* 19:204–214, 2001). C. De Wolf ("**Low carbon pathways for structural design**," **http://dspace.mit.edu/handle/1721.1/7582**) found ~35% higher materials intensity in 6–10- than in ≤5-story buildings, and that at greater than 20 stories, steel intensity can be 4X that of similarly framed low-rise buildings.

193 Z. Moussavi Nadoushani, A. Akbarnezhad, "Effects of structural system on the life cycle carbon footprint of buildings," *Energy and Buildings* 102:337–346, 2015, **https://doi.org/10.1016/j/enbuild.2015.05.044**.

194 Of course, composites are now widely used in other building elements, notably lightweight curved façades.

195 Owens Corning Infrastructure Solutions, "A hidden revolution: composite rebar gains strength," 1 Dec 2011, *Composites World*, **https://www.compositesworld.com/articles/a-hidden-revolution-frp-rebar-grains-strength**.

196 G. Pauli, "**Building with Bamboo**," ~2010, describes some impressive carbon-neutral structures, and reports that Taiheiyō Cement offers roofing and wall systems based on 75% bamboo/25% cement sheets pressed together and "now widely used in the high speed train stations of Japan." Brazilian bamboo-cement panels are mentioned in S. Surip *et al.*, "**Bamboo Based Biocomposites Material, Design and Applications**," ch. 19 in Y. Mastai, ed., *Materials Science: Advanced Topics*, 2013. Some bamboo-reinforced structural concrete applications behave well (e.g., P. Mali, D. Datta, "**Experimental evaluation of bamboo reinforced concrete slab panels**," *Construction and Building Materials* 188:1092–1100, 2018), some not (H. Archila, S. Kaminski, D. Trujillo, E. Escamilla, K. Harries, "**Bamboo reinforced concrete: a critical review**," *Materials and Structures* 51:102, 2018); bamboo and steel are not interchangeable.

197 Approximately 80% CO_2 savings in making cement would make it carbon-neutral because ~20% is reabsorbed long-term (Rissman, "**Cement's Role in a Carbon-Neutral Future**," Energy Innovation, 2021). Absorption is much faster in thin layers like screeds and mortars, or in concrete crushed by demolition. Carbonation is also faster with many alternative formulations (e.g., twice the uptake, at tripled speed, using limestone calcined clay cement with 50% supplementary cementitious materials [Habart, *et al.*, "Environmental impacts and decarbonization strategies," *Nature Reviews*, 2020]).

198 Habart, *et al.*, "Environmental impacts and decarbonization strategies," *Nature Reviews*, 2020.

199 A further frontier is emerging from new materials made from wood, such as **Inventwood.com**'s

Mettlewood, that can turn cellulosic materials into new ones with properties more akin to those of metal, but insulating and light-transmitting.

200 S. Wallis, "The Trees and the Forest of New Towers," *N.Y. Times*, 20 Nov 2019; F. Lowenstein, B. Donahue, and D. Foster, "Let's Fill Our Cities with Taller, Wooden Buildings," *New York Times*, 3 Oct 2019.

201 ZERI Foundation, "ZERI Pavilion for EXPO 2000," 2d edn., 2002, **http://www.zeri.org/ZERI/Home_files/ZERI%20PAVILION%202012.pdf**.

202 E.g. I. Nanayakkara, "Shell structures: lessons in structural efficiency for sustainable construction," Institution of Structural Engineers (London), 2020, **https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-4/shell-structures-lessons-in-structural-efficiency/**.

203 P. Block, T. van Mele, M. Rippmann, F. Ranaudo, C. Barentin, N. Paulson, "Redefining structural art: strategies, necessities and opportunities," *The Structural Engineer* 98(1):66–72, 2020, **https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-1/redefining-structural-art-strategies-necessities/**, **https://www.researchgate.net/publication/338342926_Redefining_Structural_Art_Strategies_necessities_and_opportunities**; P. Block, C. Barentin, F. Ranaudo, N. Paulson, "Imposing Challenges, Disruptive Changes: Rethinking the Floor Slab," 2019, **https://www.researchgate.net/publication/338006235**.

204 Thus in seven-floor apartment buildings, substituting hollowcore for *in situ* cast floor slabs cut foundation concrete 14% and steel 19%, column concrete 25% and steel 20%, and beam concrete 38% and steel 47% (B. López-Mesa, Á. Pitarch, A. Tomás, and T. Galleto, "Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors," *Building and Environment* 44:699–712, 2009).

205 W. Hawkins, J. Orr, P. Shepherd, and T. Ibell, "Design, construction and testing of a low carbon thin-shell concrete flooring system," *Structures* 18:60–71, 2019, **https://doi.org/10.1016/j.istruc.2018.10.006**; see also 53%–58% embodied-carbon savings and 43%–53% self-weight reductions (plus mass decompounding in supporting beams, columns, and foundations) with 6–18 m spans from W. Hawkins, J. Orr, T. Ibell, and P. Shepherd, "A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors," *Engineering Structures* 207:110195, 2020, **https://doi.org/10.1016/j.engstruct.2020.110195**.

206 The structure (detailed in *Engineering Structures*) appears to weigh 141 kg/m^2, or ~81% less than a standard 30-cm solid reinforced-concrete slab.

207 A. Liew, D. López López, T. Van Mele, and P. Block, "Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor," *Engineering Structures* 137:323–335, 2017, **https://doi.org/10.1016/j.engstruc.2017.01.075**.

208 C. De Wolf, "Low carbon pathways for structural design: embodied life cycle impacts of building structures" MIT PhD thesis, 2017, **http://dspace.mit.edu/handle/1721.1/7582, pp. 120–124**.

209 Minor differences in concrete composition between the cases have only a small effect on performance. Simple supports and an 8.1-m span are assumed, dead loads of 1.5 kN/m^2 for the steel-reinforced concrete cases and 2.0 for the carbon-fiber-reinforced folded slab, and live loads (3 kN/m^2) typical of German standards for hotels, hospitals, offices, or homes. Those live loads slightly reduce the 80% materials saving for similar roof slabs (Exhibit 4j and "Prestressed Textile Concrete," Ginkgo Textilbeton).

210 Juan Pablo Osman Letelier (Schlaich Bergermann Partner), personal communications, 18–19 Jan 2021.

211 A. Schlueter *et al.*, "3for2: Realizing Spatial, Material, and Energy Savings through integrated Design," *CTBUH J.* 2016(II), Council on Tall buildings and Urban Habitat, 2016, **https://global.ctbuh.org/resources/papers/download/2783-3for2-realizing-spatial-material-and-energy-savings-through-integrated-design.pdf**.

212 J. Benyus provides biomimicry webinars at **https://synapse.bio/blog//lightweighting-inspired-by-nature**. A typical example is M. Meyers, J. McKittrick, and P. Chen, "Structural biological materials," *Science* 339(6121):773–779, 2013, **https://doi.org/10.1126/science.1220854**. Though this paper focuses on orthodox engineering approaches, biomimicry's innovative scope is enormously wider: McKinsey Global Institute's 2020 report *The Bio Revolution: Innovations Transforming Economies, societies, and our lives* compiles ~400 applications directly worth up to $4 trillion/y over the next 10–20 years, able to cut CO_2 emissions by 7%–9% over the next few decades. A lovely introduction to biomimetic practice is the free online journal *Zygote Quarterly*. The best database is **https://asknature.org**.

213 A. Lovins, "Decarbonizing Our Toughest Sectors—Profitably," *MIT Sloan Management Review*, pp. 2–11, Fall 2021, in press.

214 *Mission Possible*, ETC, 2018, p. 101, Exh. 5.2, but probably including carsharing business models.

215 *The Circular Economy*, Material Economics, 2018, p. 157.

216 Not counting reuse and recycling, nor a 5% saving from reducing ~10–20% construction waste, and applying the same EU-to-global 0.76X scaling shown. The full circularity savings are larger (ETC's *Mission Possible* report Exh. 5.6 [p. 106] shows 22% for cement, while Exh. 5.2 [p. 101] shows 20% for material efficiency and 37% when combined with materials circulation).

217 *Mission Possible*, ETC, 2018, p. 128.

218 Comparing data from *Mission Possible* (p. 112, and p. 114 text and n. 4 reference) with 2020 IRENA and Bloomberg market-price data.

219 *Mission Possible*, ETC, 2018, pp. 167–168.

220 Pursued by industry initiatives like those listed in ETC's *Mission Possible* report, p. 165.

221 Truck-efficiency leader Mike Roeth, Executive Director of the North American Council for Freight Efficiency, "fundamentally challenge[s] stating that trucking is a 'hard to abate' sector" (personal communication, 29 Sep 2020).

222 N. Bullard, "Energy Transition's Half-Trillion-Dollar Year Is Even Better Than It Looks," Bloomberg New Energy Finance, 21 Jan 2021, **https://www.bloomberg.com/news/articles/2021-01-21/what-does-500-billion-for-clean-energy-mean-for-climate-change?sref=BC8pqjS2**.

223 *Mission Possible*, ETC, 2018.

224 A. Phadke *et al.*, "Why regional/long-haul trucks are primed for electrification now," LBNL, **https://eta.lbl.gov/publications/why-regional-long-haul-trucks-are**.

225 D. Tong *et al.*, "Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target," *Nature* 572:373–377 (2019), **https://www.nature.com/articles/s41586-019-1364-3**.

226 Often this requires not just integrative redesign but also transformations of institutional and physical infrastructure (S.J. Davis *et al.*, "Net-zero emissions energy systems," *Science* 360(6396):eaas9793, 29 Jun 2018).

227 Perhaps the most detailed US assessment showed how US electric end-use efficiency, deployed at a historically reasonable pace, could quadruple by 2050 at an average cost one-tenth today's retail price of electricity (A. Lovins and

RMI, *Reinventing Fire*, 2011, p. 204), not including most integrative design (A. Lovins, "How big is the energy efficiency resource?," *Environmental Research Letters*, 2018).

228 *Mission Possible*, ETC, pp. 112–114.

229 *World Energy Transitions Outlook: 1.5°C Pathway*, International Renewable Energy Agency, Preview, 16 Mar 2021, **https://irena.org/publications/2021/March/World-Energy-Transitions-Outlook**.

Amory B. Lovins, *Profitably Decarbonizing Heavy Transport and Industrial Heat: Transforming These "Harder-to-Abate" Sectors Is Not Uniquely Hard and Can Be Lucrative*, 2021, https://www.rmi.org/profitable-decarb/

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