Energy efficiency The rest of the iceberg

Efficiency is the energy user's most abundant resource, with expanding returns from radical redesign. It is a disruptive technology in its own right.

Amory B. Lovins

EFFICIENCY

SHIPS

RENEWABLES

SAVINGS

ENGINEERS

CHINA

I live on, or more precisely in, a passive solar banana farm. Banana crops numbers 48-54 are currently ripening in the 85 square metre semitropical jungle in the middle of my house. Last year, crops 46 and 47 harvested themselves when their 30 kilogram weight pulled down the tree.

Yet this house is 2,200 metres high in the Colorado Rockies near Aspen, where temperatures have dipped as low as –44 degrees Celsius, continuous midwinter cloud has lasted up to 39 days, and the growing season between hard frosts used to be six weeks. Locals joked about having two seasons, winter and July, until what Hunter Lovins calls 'global weirding' added August.

My house also has no conventional heating system. It's roughly 99% passively heated by more than doubled thermal insulation, airtight construction, heat-recovery ventilation, and superwindows that insulate like 14 (or even 22) sheets of glass, look like two, and cost less than three. Until 2009, the remaining 1% of the space heating came from two stoves occasionally burning wood or obsolete energy studies, but five winters ago we decommissioned those woodstoves – combustion is so 20th-century – and replaced them with surplus active-solar heat.

Saving 99% of this house's space-heating energy lowered its 1982-84 construction costs by about $1,100 (€790), because the eliminated conventional space-heating system would have cost more up front than the heat-saving technologies that displaced it. Reinvesting that saved capital cost, plus $6,000 (€4,300) more, in water- and electricity-saving technologies then saved 99% of the water-heating energy, half the water, and 90% of the household electricity. All the savings recovered their total 1% extra capital cost in the first 10 months, and in the next decade will have paid for the entire building. They also made all-solar power supply affordable.

This is the kind of project we at Rocky Mountain Institute (RMI) find instructive. RMI is an independent, non-partisan, non-profit think-and-do-tank that drives the efficient and restorative use of resources. We employ rigorous research to develop breakthrough insights. We then convene and collaborate with diverse partners, chiefly large firms, to speed and scale solutions for a clean, prosperous, and secure energy future. Thus we create abundance by design.

This superefficient building, which was also RMI's initial headquarters during 1982–2000, illustrates highly integrative design, getting multiple benefits from single expenditures: its central arch, for example, has 12 functions but only one cost. The building helped to inspire more than 32,000 passive buildings in Europe which, like ours, have no conventional heating system but roughly normal construction cost, since experience shrank their premium from an initial 10-15% to zero, plus or minus a few per cent. Similarly integrative design has eliminated homes' air-conditioning needs and reduced construction cost at up to 46 degrees Celsius in California (not an upper limit), and saved 90% of air-conditioning energy in steamy Bangkok at normal construction cost, both achieving better comfort. Almost everyone in the world lives in a climate somewhere between Bangkok's and mine.

Big buildings have surprising efficiency potential too. The 2010 retrofit design I co-led at the Empire State Building is saving two-fifths of its energy with a three-year payback. That's the same payback offered by a major energy service company, but with six times its savings, because that firm optimised individual components in isolation, while we optimised the entire building as one system. Remanufacturing all 6,514 double-glazed windows onsite into superwindows that would insulate four times better and be nearly perfect in admitting light without unwanted heat, plus more conventional improvements, together cut peak cooling loads by one-third. Renovating smaller chillers rather than adding bigger ones then saved enough capital cost to pay for most of the improvements. Three years later, an RMI retrofit of a large Federal building in Denver saved 70% of its energy, again with good economics. Similarly, Peter Rumsey's and Rohan Parikh's new office designs for Infosys in Bangalore and Hyderabad cut energy use by 80% with lower capital cost and higher occupant satisfaction and productivity.

Such results stem less from technology than a new design mentality – asking different questions in a different order. If you asked an engineer how much insulation my cold-climate house should have, you'd probably be told, "Just the amount that will repay its extra cost from the heating fuel it saves over the years." The engineering textbooks all agree.

But they're wrong, because this methodology omits the immediate, and avoidable, capital cost of the heating equipment. Most engineers make the same mistake (and others) when designing buildings, vehicles and factories. In our latest $40+ billion worth of new and existing industrial redesigns, including seven for Shell, my RMI colleagues and I found practical energy-saving potentials typically around 30-60% with retrofit paybacks of a few years, or in new construction, about 40-90% with nearly always lower capital cost. This wouldn't be possible if they'd been optimally designed from the start.

Continuous change

Such examples of today's energy-efficiency potential[1] are actually just a few frames in a very long movie. Ever-improving technologies, design methods, financing and marketing channels, business models and public policies now make potential energy savings ever cheaper. Saving electricity today costs about two-thirds less than it cost in 1980. Costs continue to drop with no end in sight and new vistas continually unfolding. As Dow found by saving $9 billion (€6.5 billion) so far on a $1 billion (€0.7 billion) efficiency investment, enculturating and cultivating energy efficiency often reveals new opportunities faster than engineers use up the old ones.

Efficiency then becomes an expanding and renewable resource with returns that, far from relentlessly diminishing, often expand, so bigger savings cost less, not more – a design innovation more disruptive than any technology.[2] RMI's practice has demonstrated this potential not just in big industrial projects but also in more than 1,000 buildings and in various automotive and ship designs. The methodology can be taught.[3] We're starting to spread it and overhaul design pedagogy and practice. Our modest goal is the non-violent overthrow of bad engineering.

Efficiency is not a binary attribute you have or lack; its goalposts move continuously. In the late 1990s, my house was turning into a museum of 1983 technologies, so we updated them, not because there was a business case – hardly any energy was left to save – but to check how much better they've become. From initial monitoring of several hundred data streams, we've found so far that the monitoring system is probably using more energy than the lights and appliances.

Today's technologies and design methods can do almost everything with far less energy, and ultimately with almost none. Yet they're not yet widely taught, used, or even considered. This book contains 14 essays on energy supply but just this one on efficiency. Even firms as aware as Shell typically devote a similarly lopsided ratio of analytic and strategic attention to energy supply versus efficient use.

Yet the 118% rise in US energy productivity since 1975 (mostly from technical improvements, some from compositional change, a little from behaviour) was equivalent by 2012 to a 'resource' 1.85 times that year's US oil and gas consumption. The USA and several EU countries, notably Germany and Denmark, now have growing economies but shrinking electricity use. US weather-adjusted electricity use per dollar of real GDP fell by 3.4% in 2012 alone. US electricity and petrol use both peaked in 2007.

Perhaps developing economies will grow faster than they become efficient. But that's a bet, not a given. Already, many are leapfrogging from kerosene and incandescent lamps to LEDs, just as their televisions leapt from vacuum tubes to modern microelectronics and their telecommunications skipped over wireline phones. If developing countries exploit the advantage that building things right is easier, faster and cheaper than fixing them later, they could shake off the prediction of their slow slog akin to rich countries' historic development patterns and refute the forecasted high energy demand that suppliers are investing to meet.

Something similar is happening in China, which during 1976-2001 cut its energy intensity (primary energy used per unit of real GDP) by more than 5% per year, a feat probably unrivalled in world history. After a five-year hiatus, savings nearly as brisk have resumed. In 2012, China's efficiency and renewables displaced so much electricity that coal plants were run much less frequently, adding more new electricity from non-hydro renewables than from all fossil-fuelled and nuclear plants combined. (China made more electricity from wind than from nuclear power, and in 2013, added more solar capacity than the US has.) Similarly, US 2012 energy savings were nearly twice as important as natural gas in displacing coal-fired electricity.

Bloomberg New Energy Finance and ren21.net track the global progress of modern renewable energy in admirably granular detail, finding that renewables other than big hydro dams added more than 80 billion watts and received a quarter-trillion-dollar investment in each of the past three years. But annual global investment in saving energy (about $150-300 billion or €100-200 billion in 2011) was first credibly estimated only in 2013, when the International Energy Agency (IEA) found that 1974-2010 energy savings in 11 IEA countries totalled 1.5 times their oil use.[4]

ALUMINIUM

CARBON FIBRE

DRILLING

FORECASTING

BATTERIES

TRANSPORT

Statistical experts track energy's volumes and prices in exquisite detail, yet devote dramatically less effort to tracking savings. Nobody knows how much energy the world is saving. Being less visible than the submerged part of an iceberg, efficiency poses a hidden peril to navigators of supply-side waters, because when supply outruns demand, prices crash as they did in the mid 1980s, and overinvested suppliers can sink without even knowing what they ran into.

In short, efficiency is "generally the largest, least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services".[5] It is the energy area ripest in risks for suppliers – and nowhere more strikingly and unexpectedly than in motor vehicles, the world's biggest user of oil.

The missing automotive story

Demand for motor fuels could shrink or even disappear in the next few decades as radical design and business innovations transform the manufacture of cars and light commercial vehicles – driven not by regulation but by customer demand, powerful competitive forces, and emergent realignment of energy strategy in China, where RMI's *Reinventing fire* synthesis of advanced efficiency and modern renewables[6] is informing the 13th Five Year Plan. China's polluted air is strongly reinforcing the drivers of oil risk and cost, climate change, and a rapidly growing but not yet globally competitive automotive industry.

The opportunity is rooted in vehicle physics. A typical US car uses roughly 100 times its own weight every day in ancient plants, very inefficiently converted from primeval swamp goo into trapped, discovered and extracted oil. Yet only about 0.3-0.5% of the fuel used by the car ends up moving its driver; about 87% is lost in the powertrain (and minor accessory loads) before reaching the wheels. Of the 13% delivered to the wheels, 7% heats the air that the car pushes aside or heats the tyres and road, and only 6% accelerates the car. That two-tonne steel vehicle weighs more than 20 times as much as its driver, and for the past quarter-century has gained weight twice as fast in an epidemic of automotive obesity.

Manufacturers of cars and light commercial vehicles have traditionally focused on wringing slightly more work from the powertrain (the engine plus the driveline that delivers its torque to the wheels) because that's where most of the losses occur. But two-thirds of the energy needed to move a typical US car (its 'tractive load') is actually caused by its weight, so ultralighting – using far lighter but stronger materials and smarter designs that sustain or improve crash safety – is the most effective way to save fuel. Combined with better aerodynamics and tyres, it can cut tractive load by half to two-thirds. Each unit of energy thereby saved at the wheels subsequently saves six more units previously lost delivering that energy to the wheels, generating seven units of total fuel savings at the tank. Thus 'vehicle fitness', and capturing its snowballing weight savings with 'mass decompounding' and radical simplifications, can cut fuel needs by roughly half to two-thirds. This then makes electric propulsion affordable, displacing the remaining motor fuel while capturing electric traction's inherent advantages – it is efficient, powerful, modular, reliable, compact, quiet, controllable, clean and fairly cheap. Furthermore, electric traction offers far richer design flexibility and rapid evolutionary potential than the mature Victorian mechanical arts.

Accelerating a lighter vehicle needs less force. Shrinking its powertrain (especially if electric and hence high-torque) saves capital cost that then helps pay for the lightweighting and streamlining – just as eliminating my house's furnace helped pay for the efficiency that displaced it. Needing severalfold fewer batteries or fuel cells for the same driving range can speed, by a decade or two, the adoption of electric propulsion (plug-in hybrid, battery-electric, or fuel-cell). Lithium-ion battery packs became 43% cheaper from 2010 to early 2014, another 30% or more drop is on the way, and other promising battery chemistries are emerging. The car- and truck-building industry's two hottest trends for the past five years – lightweighting and electrification – both compete and co-operate. Electrification might even become inexpensive before ultralighting, but regardless of their sequence, combining both captures strong synergies.

The traditional strategy of first making batteries and fuel cells cheaper through better technology proved difficult without high sales volumes driven by a compelling value proposition. But using vehicle fitness instead to make batteries and fuel cells fewer reduces their cost equivalently. This then builds sales volumes that make the components cheaper, achieving the same ultimate goal with less time, cost and risk. This idea, so simple that it was slow to take hold, entered the US Department of Energy's policy in

2013 and is now in various stages of adoption by four to seven automobile manufacturers on several continents, sped by such agile and uninhibited competitors as Tesla Motors.

Limited foresight

Nonetheless, most industry and government analysts continue to assume only slow and incremental lightweighting, efficiency gains and electrification. In 2009, the US National Research Council again declined to examine ultralighting and its enabling of affordable electrification via whole-vehicle design optimisation.[7] In 1991, GM had built the sporty 100 miles per US gallon (2.3 litres per 100 kilometres) Ultralite carbon-fibre concept car. In 2000, a complete virtual design of a luxury midsize SUV (by RMI's Hypercar spinoff with two European Tier One engineering firms) had startled manufacturers with 3.6-6.3-fold higher efficiency (using petrol or hydrogen respectively) and a calculated one-to-two-year retail payback.[8] Repeating a long history of being rapidly outpaced by market developments,[9] the 2009 NRC report was followed within two years by BMW and VW announcements that in 2013 they would begin series production of cars integrating ultralight carbon-fibre bodies with electric drives. Those vehicles are entering the market in 2014. Their carbon-fibre-body manufacturing methods now face competition from 16 other commercialised processes.[10]

In 2011, RMI published a rigorous and independent zero-US-oil-demand-in-2050 scenario with forewords by the President of Shell Oil and the then Chairman of Exelon.[11] Yet a year later, the US National Petroleum Council's (NPC's) transportation-fuels study[12] forecast only medium or high automotive fuel demand, because its integration model, ignoring expert peer-reviewers' objections, limited 2050 weight reductions to just 30%. More than a dozen vehicles had already demonstrated greater weight reductions by 1988, and another 19 – including five in production and four in pre-production prototypes – by 2010.[13] In 2007, Toyota's 420-kilogram carbon-fibre 1/X plug-in-hybrid concept car – not built for amusement – had reduced weight by 69% with the interior volume of a Prius but half its fuel use – and the world's largest maker of carbon fibre had announced a ¥30 billion (€215 million or $300 million) factory to "mass-produce carbon-fibre car parts for Toyota".

The NPC study's leaders ignored the transformational potential revealed by these more than 30 examples. Their innovation-resistant analysis tacitly assumed the global automotive industry won't continue to develop very lightweight cars and light trucks that not only save most of their fuel but also make electrification rapidly affordable, displacing the rest of their fuel. Yet probably every significant manufacturer has such efforts under way. Such vehicles could beat legally mandated efficiencies by 2-4-fold, achieving 1-2 litres per 100 kilometres rather than 4-8, and better meet both makers' and customers' requirements without compromise. Retail customers could see payback times below three years at low US fuel prices (or immediate paybacks using temporary size- and revenue-neutral 'feebates' that let car buyers value life-cycle fuel savings as society does). Manufacturers could achieve 80% lower capital intensity, systematic de-risking, and far greater manufacturer and dealer margins. Other players in this intensely competitive global industry would have to follow suit or lose share. Why wouldn't developing countries, the only source of forecast growth in world oil demand, want to leapfrog to such advantageous vehicles too? What would this mean for fuel suppliers?

Drilling under Detroit

In the USA alone, RMI's *Reinventing fire* synthesis showed that such superefficient electrified vehicles could realistically eliminate automotive motor-fuel demand by 2050, saving about 1.5 Saudis' or 0.5 OPEC's worth of oil at an average cost of $18 per barrel (in dollars of 2009). How many oil companies' investment plans include this contingency?

If you went to the ends of the earth to drill for very expensive oil that might not even be there, while someone else brought in more than 8 million barrels per day of $18 per barrel 'negabarrels' from the 'Detroit Formation', wouldn't you feel embarrassed or perhaps broke? Shouldn't we drill the most prospective plays first? And might you want to invest in the automotive revolution, making less money on oil but more on vehicle sales – a hedge we call the 'negabarrel straddle'?

Even without the accelerating carbon-fibre revolution, familiar light-metal structures offer impressive gains. Ford's 2015 all-aluminium F150 pickup truck (America's best-selling vehicle) shrank its engine displacement by 31-57% helping to pay for the aluminium. A 1997 proprietary study by RMI and a major manufacturer found this approach could make a high-volume aluminium-intensive production car more efficient than a Prius hybrid but with a

ELECTRIC TRACTION

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FUEL CELLS
COMPOSITES
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BIOFUELS
TRACTORS

conventional non-hybrid powertrain, three-fifths higher fuel economy, higher manufacturer and dealer profits, and a two-year retail payback. Similarly, RMI spinoff Bright Automotive's aluminium-intensive 2009 IDEA commercial fleet van's plug-in-hybrid driving prototype saved nearly a tonne of weight, considerable drag, and hence half its batteries. Its fuel-efficiency gain from 17-19 to 1.5-3.4 litres per 100 kilometres offered fleet buyers a compelling business case with no subsidy.

Carbon-fibre and other advanced polymer composite structures are less familiar and commercially mature than metal ones, but offer higher performance and crashworthiness, far simpler manufacturing and, with astute design and manufacturing choices, comparable or lower total manufacturing cost at scale. The resulting two- to threefold smaller tractive load could enable all kinds of advanced powertrain.

For example, the fuel-cell midsize-SUV virtual design from 2000 mentioned above needed only 3.4 kilograms of 345-bar hydrogen, in 137 litres of safe off-the-shelf 1990s-vintage carbon-fibre tanks, to drive 530 kilometres. These two-thirds-smaller tanks could be easily packaged, leaving plenty of space for people and cargo, without needing a breakthrough in storage (such as the difficult 700-bar tanks now being introduced by several makers of heavy steel vehicles). The fuel cell too would become two-thirds smaller, justifying three times higher cost per kilowatt. A typical 80% experience curve – so a doubling of cumulative production volume cuts the real cost by 20% – would then need some 32 times less production to reach a competitive price point, cutting a decade or two off deployment times. The key was a 53% lighter carbon-fibre vehicle so efficient that its motorway cruise speed needs less energy delivered to the wheels than today's heavy steel SUVs use on a hot afternoon just to run the air conditioner. That 14-year-old design could be much better done today. Hydrogen economics (using forecourt reformers except where wind power is cheap enough for electrolysis) also look sound, and practical, profitable hydrogen infrastructure solutions were worked out in 1999.[14]

In short, a disruptive design and manufacturing strategy integrating ultralighting, excellent aerodynamics and tyres, superefficient accessories and electric traction could improve automotive efficiency by an order of magnitude without compromising safety, handling, acoustics, acceleration, cost, styling or other customer attributes. Twenty-three years into this revolution, its technical basis is now looking clearly feasible, its competitive advantage enticing, and its market success plausible. By 2014, RMI and trade allies had boosted its prospects by catalysing two potential game changers: a new supply chain for volume-produced carbon-fibre automotive structures, and Chinese strategic exploration of an automotive leapfrog initiative that, if adopted, could transform the global competitive landscape.

Wider implications

Such affordable electric vehicles' distributed storage, intelligently linked to electric grids, could help integrate variable renewable generators, making the automotive and electricity problems much easier to solve together than separately. And we don't need a smart grid to use a dumb grid in smarter ways. My battery-electric car (whose registration plate, OFF OIL, is not aspirational but factual – perhaps unique among NPC members) is solar-recharged by a circuit that adjusts its charge rate every second between 0 and 7 kilowatts according to real-time grid frequency. This dispatches to the US Western Interconnect a valuable ancillary service called 'fast regulation'. If my utility paid me properly for this service, I'd make several dollars' profit every night just by recharging my car.

Such technological and design innovations can also inspire new business models. For example, David Moskovitz of the Regulatory Assistance Project notes that vehicle manufacturers could sell electrified vehicles at a deep discount – boosting sales – if the buyer agreed that when each vehicle is plugged in and parked, the manufacturer could control it and conduct profitable electrical transactions with the grid, providing invisible settlements and using its aggregation volume to negotiate a good sales price while guaranteeing the owner uncompromised driving capability and experience.

Even more disruptive emergent business models are leading some manufacturers to consider a shift from selling cars and trucks to leasing mobility and access services. Cars, typically the second-biggest US household asset, sit idle about 96% of the time, inviting shared transport or electrical transactions. The winners may well be firms that shift vehicles from a revenue source to a cost of delivering desired access and mobility. Like the classic 'solutions economy' approach,[15] this could align provider with customer interests, rewarding both for doing more and better with less for longer. Providers – of vehicles, finance, fuel or information services – that seriously adopt this approach could put intolerable market pressure on laggards.

Even if this didn't occur, the USA could provide the same access with 46-84% less driving just by combining proven methods for IT/transport integration, charging drivers for road infrastructure by the kilometre not the litre and encouraging smart spatial planning so more customers are already where they want to be and needn't go somewhere else. Any savings from videoconferencing, virtual presence and other ways to move only electrons and leave the heavy nuclei at home, or from better freight logistics, more-localised manufacturing, and dematerialisation, would displace even more fuel. During 2005-2013, Walmart's giant truck fleet cut its fuel use per case by 46% without yet using many available options. Some jurisdictions are also moving toward making markets in 'negatrips' and 'negamiles', so all ways to travel, or not need to, can compete fairly. This could permit dramatically reduced physical mobility with fuller and fairer access, and enable a potential shift of drivers' largely socialised costs from the whole population (about a third of which, in the USA, is too old, young, poor or infirm to drive) to drivers themselves, so they get what they pay for and pay for what they get.

Other transport

Heavy trucks, the second-biggest oil user, can double their efficiency at a very attractive cost by improving aerodynamics, tyres, weight and powertrain.[16] That doubling becomes a tripling with 'turnpike doubles' – two trailers per tractor – linked in proven ways that improve safety and stability and reduce road wear.[17] These shifts are straightforward technologically but not institutionally, especially because tractors and trailers are typically made by different firms whose business models don't consistently reward efficiency or integration. Today's typical US Class 8 truck efficiencies of roughly 50 tonne-kilometres per litre could thereby rise to about 129 tonne-kilometres per litre or 2.6 times the initial value. That factor could reach or exceed 3.0 with better auxiliaries, accessories and refrigeration where present; hybrid drive and regenerative braking; idle elimination by using an auxiliary power unit when parked rather than idling the big diesel engine; and optimising driver training and driving speed. Beyond that tripled efficiency, if lighter, smaller, cheaper, fully digital diesel engines fulfil their initial lab- and road-test promise,[18] it may also become possible to make today's truck diesels dramatically more efficient, clean, small, light, cheap and fuel-flexible.

The number three oil-burner, aeroplanes, already saved 82% of their fuel per seat-kilometre during 1958-2010, but comparable or larger gains still lie ahead. A Lockheed-Martin Skunk Works tactical-fighter airframe designed in the mid 1990s – 95% carbon-fibre composite, one-third lighter, two-thirds cheaper – illustrates lightweighting potential in commercial jets, where removing 1 kilogram is worth about $2,000 (€1,500) present value. Boeing, NASA and MIT have designed tube-and-wing and blended-wing-body aeroplanes 3-5 times more efficient than today's jet fleet, still burning kerosene or equivalent drop-in-replacement advanced biofuels (slated for US Navy delivery at oil-competitive prices starting in 2015). Ultimately, with new airport fuel infrastructure, 'cryoplanes' exploiting liquid hydrogen's very light weight (more important than its greater bulk – that's why it's the best rocket fuel) may raise that saving to six- or seven-fold, with kerosene-like economics but better safety.

From motorcycles to trains and buses to ships, similar integration of advanced materials, powertrains, hydrodynamic surfaces and controls, other components, and system operations can dramatically reduce energy use and improve safety and performance. For example, RMI has co-led three analyses finding an economically attractive potential to save about half the 'hotel load' and a third of the total energy use of diverse bluewater ships. As with aeroplanes, further savings may emerge from promising innovations in hydrodynamics – notably laminar vortex flow[19] – often inspired by imitating nature's design (the science and art of 'biomimicry'[20]). And new micromodular structures could offer order-of-magnitude weight savings beyond today's ultralighting, without even invoking more-exotic materials.[21]

Overall implications for transport

Reinventing fire found that just the straightforward and currently feasible gains in vehicle technology and design mentioned above, modestly reinforced by more productive use of vehicles, could enable a 2050 US economy with 158% higher GDP than in 2010, 90% more automobility, 118% more trucking and 61% more flying – without using any oil. The 1-2 litre-equivalent per 100 kilometres electrified

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ultralight cars could use any mixture of hydrogen fuel cells, electricity and advanced biofuels. Heavy trucks and aeroplanes could realistically use advanced biofuels or hydrogen. Trucks could even burn natural gas. But no vehicles will need oil. Any biofuels the USA might need, at most 3 million barrels per day, could be made two-thirds from wastes, without displacing cropland or harming climate or soil. The land-use and other problems of large-scale biofuel feedstock would be avoided by superefficient use, leaving a very diverse portfolio of competitive options – a long-term mix that cannot but need not be known in advance.

Reinventing fire found a 17% internal rate of return for moving US mobility completely off oil by 2050, assuming that carbon emissions and all other hidden or external costs are worth zero – a conservatively low estimate. The required technologies all provide a more than 15% per year real return in trucking or a less than three-year simple payback to the car buyer. The average cost of saving or displacing oil for US mobility would be roughly $25 per barrel (in 2009 US dollars levelised at a 3% per year real discount rate) – a small fraction of today's fuel price. This implies a $4 trillion (€3 trillion) net-present-value US saving potential – or about $12 trillion (€8.5 trillion) if we added just the economic and military costs of US oil dependence, excluding any harm to health, safety, environment, climate, global stability and development, or national independence and reputation.

Since burning oil, three-fifths for transport, releases two-fifths of global fossil-fuel carbon emissions, this implies that a similar fraction of those emissions can be abated not at a cost but at a profit, because efficiency costs less than fuel. The same turns out to be true for virtually all other carbon emissions too.

For example – and importantly for natural gas's prospects in electricity generation, since buildings use nearly three-quarters of US electricity – *Reinventing fire* showed how integrative design, modern technologies and proven financing and delivery methods applied at historically reasonable rates could triple to quadruple the energy productivity of US buildings by 2050 with a 33% internal rate of return (IRR). Industrial energy productivity could double with a 21% IRR. All analysed improvements meet normal commercial hurdle rates for the respective sectors.

The policy innovations needed to enable and speed these developments can all be done in the USA administratively or at a subnational level (where most energy policy has long been made anyway). The only policy needing an Act of Congress – harmonising federal highway standards to modernise heavy trucks' size, weight and multi-trailer rules – could be omitted with only a 0.26 million barrel per day foregone saving.

The electricity industry faces even greater institutional challenges as 21st-century technology and speed collide with 20th- and 19th-century rules, institutions and cultures. Some devotees of central thermal power stations don't yet even consider the rapidly emerging distributed renewables a competitive threat, even though they've taken about half of the US, two-thirds of the European Union, and one-third of the Chinese market (with big hydro another third). Many still claim that renewables can do little without a breakthrough in cheap bulk electrical storage; yet without adding bulk storage, four European Union countries with modest or no hydropower generated about half their 2013 electricity consumption from renewables (Spain 45%, Scotland 46%, Denmark more than 47%, Portugal 58%). Denmark and Germany (25% renewable) have Europe's most reliable electricity, about tenfold better than America's.

The big picture

Quadrupling US electrical productivity using the best technologies from around 2010 and moderately integrative design has an average levelised technical cost of about $6.40 (€4.60) per megawatt-hour – far below the short-run marginal cost for any non-renewable generator. Even with suboptimal design and implementation, which raise many utilities' efficiency costs to about $20-30 (€14-22) per megawatt-hour, few supply-side projects can withstand such competition.

Reinventing fire found that running a 2050 US economy 2.58 times bigger than that of 2010 with no oil, coal or nuclear energy and one-third less natural gas could cost $5 trillion (€3.6 trillion) less in net present value than business as usual, emit 82-86% less carbon, require no new inventions or Acts of Congress and be led by business for profit – including making its electricity system 80% renewable, half distributed and highly resilient. This entire bundle yields a 14% IRR based on private internal cost alone, and could be enormously higher when counting even a shortlist of its vast external benefits. Yet few hydrocarbon or electricity firms are preparing for such a future.

Around 1999, using a variety of logics, some far-sighted analysts began forecasting 'peak oil' – not in supply but in demand, with global oil demand peaking as early as this decade, and then declining. Like whale oil in the 1850s, oil is becoming uncompetitive even at low prices before it becomes unavailable even at high prices. The whalers were astounded to run out of customers before they ran out of whales. But in the nine years before Drake struck oil in Pennsylvania, at least five-sixths of the lighting market long dominated by whale oil went to coal-oil and coal-gas competitors, and 20 years after Drake, Edison's electric light began to displace those too. Thus were the remnant whale populations saved by technological innovators and profit-maximising capitalists.

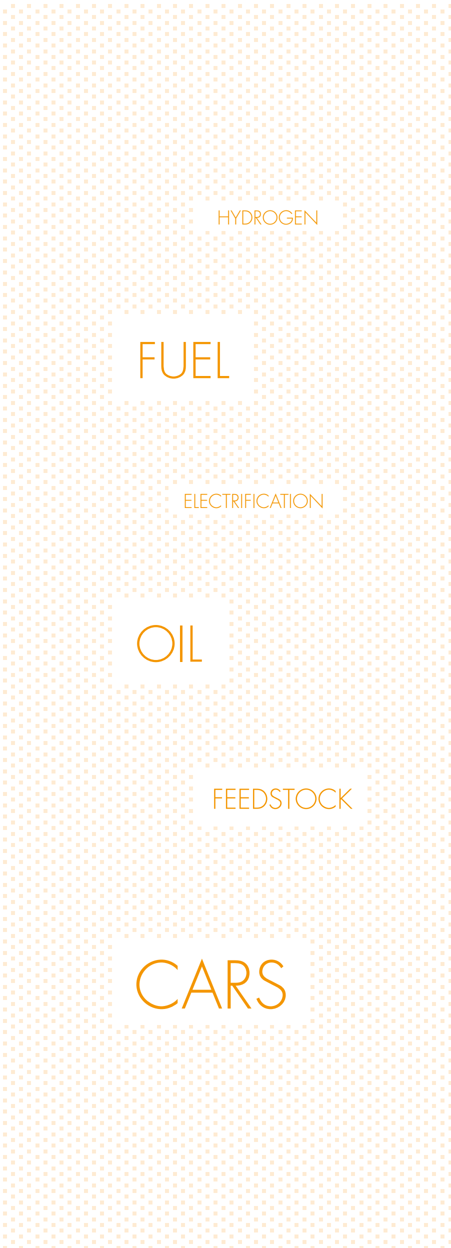
As demand-side innovation threatens oil sales, and as new US gas-combined-cycle power plants become ever costlier than new wind and solar power, the oil and gas industries are coming under the stress of upside-down marginal economics. In the past decade, while oil prices nearly tripled from $40 to $110 per barrel, oil majors' return on capital employed fell by one-third, and for over half of them in 2013, it fell to or below 10% due mainly to higher cost, risk and complexity.[22] In 2013 alone, ExxonMobil, Chevron and Shell invested more than $120 billion (€85 billion) upstream, more than the cost of putting a man on the moon, bringing their five-year total above a half-trillion dollars; yet their output and profits declined.[23]

Oil exploration and production's capital intensity is spiralling beyond the ability to sustain it; the revenue model is broken. Elephant projects are less profitable and more risky than legacy output, together depressing risk-adjusted returns. Fragile and utterly unforgiving megaprojects, each risking tens of billions of dollars with no revenue for many years, can hazard the reputation if not the stability of some of the world's largest firms.

Furthermore, the industry's fundamentals are discouraging and deteriorating. International oil companies have extremely high capital intensity, decadal lead times, and high technological, geological and political risks. Parastatals own about 94% of global reserves and can take or tax away the companies' remaining 6% at any time. Resource owners also force the majors into riskier and costlier plays even as investors demand lower risks and higher returns. The industry is politically fraught, unpopular, interfered with, and reputationally damaged by its worst actors. Its service companies are becoming formidable competitors. Its permanent subsidies are coming under greater scrutiny. It's a price-taker in a volatile market. Much of the reserve base underlying its valuation may be unburnable, potentially wiping trillions off balance sheets. The costly frontier reserves that get half the supermajors' marginal investments are also economically stranded assets – at least four times costlier than demand-side competitors, and increasingly challenged even by some supply-side competitors. Thus the business model's prime imperative – value must exceed price must exceed cost – is being remorselessly squeezed at both ends.

What a recipe for headaches! Why would anyone want to stay in such an enterprise? Isn't oil – like airlines – a great industry but a bad business? No wonder some savvy investors are starting to shift their money into assets with rapid growth, wide benefit, solid consensus, modest risk and durable value. Energy efficiency and renewable energy lead the pack. Increasingly they poach investment, momentum and people from the deep talent pools of major oil companies. Even RMI's CEO is a 10-year Shell veteran.

Natural gas differs from oil, but not much, with high capital intensity, price and counterparty risk, and geological risk. After the Henry Hub gas price dipped below $2 (€1.40) per gigajoule in 2012, many pundits insisted US gas price volatility was history. Less than two years later, the price was steadily over $4 (€3) and had spiked to nearly $8 (€5.70). Moreover, 'cheap' gas actually costs $1-3 (€0.70-2) more than its spot price on a risk-adjusted basis.[24] That is, a fair comparison with stably priced alternatives, efficiency and renewables, must add to gas's commodity spot price the market value of its price *volatility*, which is discoverable from the straddle in the options market and likely to increase if wellhead gas becomes cheap and stably priced (because that drives liquefied natural gas exports, petrochemical pivot to gas, and exploitation of downstream-bottleneck rents). The result – not $3-4 but $6-8 gas – is consistent with futures markets. It's logical because markets equilibrate: if you want $6-8 gas, assume $3-4 gas and use it accordingly. And it's reasonable because fracking's eight main kinds of risk and uncertainty, which will take perhaps a decade to resolve, are fairly unlikely all to come right. So fracking creates an important story about affordable and abundant energy for the long term



SUPPLY-SIDE INVESTMENTS

RISKY

COMPLEX PROJECTS

MENDELEEV

CARBON CONCERNS

ULTRALIGHT

– but that story is less about gas than about its physical hedges, efficiency and renewables, which are outpacing and increasingly outcompeting it.

Whither hydrocarbons?

Any durable way forward for applying the hydrocarbon industry's unique and remarkable capabilities must begin with a mature assessment of these conditions. It must soberly compare competitive prospects and risks on a timescale commensurate with the lives of proposed supply-side investments. And it must seek ways to redeploy assets and skills to thrive in and help to shape the emerging new world of radical efficiency and diverse, distributed, renewable, resilient supply.

International oil companies have unusual, if not unique, skills in organising very large, complex projects. How far can those skills be turned to a mix of medium-sized, moderately complex projects (such as offshore wind power complexes) while morphing increasingly into the financing of many smaller projects with short lead times, low risks, and fairly fast paybacks (such as efficiency, combined heat and power, and many modern renewables)?

What if extremely capital-intensive, risky, long-lead-time upstream investments were diverted to a far less capital-intensive, low-risk, short-lead-time portfolio of non-hydrocarbon energy investments? Mightn't one expect a rather quick turnaround in risk-adjusted returns? And mightn't oil companies with the courage to undertake this wrenching change gradually evolve toward becoming normal companies, valued not materially on the questionable book value of their hydrocarbon reserves (which they could deplete or sell) but just on their free cash flow, their net earnings, and their leadership, management, technical, marketing and financial skills? This is not to say that hydrocarbons lack substantial future value; it is rather to question whether that value will rise or fall under the twin assault of carbon concerns and of cheaper, better ways to do the same tasks. This uncertainty creates such an existential question that avoiding it, by strategies offering low cost and risk, would seem prudent.

A saving grace could also be that the hydrogen in hydrocarbons is generally worth more without than with the carbon, even if nobody pays to keep carbon out of the air. Because hydrogen can be used so much more efficiently than hydrocarbons one will generally make more money extracting hydrogen in a reformer than adding hydrogen in a refinery. Thus hydrocarbons in the ground could remain, as Mendeleev foresaw, precious as a feedstock (competing with biofeedstock and more productive use of molecules) but far too valuable to burn. That is, their highest and best use is as feedstock and as a hydrogen source; their lowest-value use is as fuel – the market most suppliers emphasise today.

The accelerating efficiency revolution challenges many fundamental assumptions that underlie oil-industry strategy. Many in the industry do not yet understand that their competitors are not other upstream players but rather thermal insulation, ultralight electrified cars and integrative design. But it's clear that customers will increasingly realise they'll get better service at lower cost by buying less energy and using it far more productively. It's generally a smart strategy to sell customers what they want before someone else does. All the rest is detail.

Amory B. Lovins, an American physicist, is co-founder and Chief Scientist of Rocky Mountain Institute (RMI). He is an ex-Oxford don, honorary US architect, and Swedish engineering academician. He has written 500+ papers and 31 books, taught at 10 universities, redesigned numerous buildings, vehicles and factories, and advised major firms for 40+ years in 60+ countries. A member of the National Petroleum Council (NPC), he advises the US Chief of Naval Operations. He received the 'Alternative Nobel', Blue Planet, Volvo, Zayed, Onassis, Nissan, Shingo and Mitchell Prizes, MacArthur and Ashoka Fellowships, 12 honorary doctorates, and the Heinz, Lindbergh, National Design and World Technology Awards. In 2009, *Time* named him one of the world's 100 most influential people, and *Foreign Policy*, one of the 100 top global thinkers. He has had a loose advisory association with Shell since 1973.

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This essay is published in:

Gert Jan Kramer and Bram Vermeer (eds.). *The colours of energy: Essays on the future of our energy system*, which is published on the occasion of the centennial of Shell Technology Centre Amsterdam, on July 2, 2014. A commercial edition is planned.

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PUBLISHER
Shell International B.V., Amsterdam, the Netherlands

www.shell.com

ISBN 978-90-9028343-2