Reinventing Fire: Physics + Markets = Energy Solutions

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At Rocky Mountain Institute, we're practitioners, not theorists. We do solutions, not problems. We do transformation, not incrementalism. So in 2009–11, 60 colleagues and I, with much help from industry on both content and peer review, created a detailed, rigorous, well-documented, and transparent "grand synthesis" of a pragmatic, market-driven, business-led energy solution for the United States.[1] Our findings seem relevant to many other societies, and are currently being adapted and replicated with three distinguished partner organizations to inform China's 13th Five Year Plan in 2015.[2]

America's peculiar public energy conversation, if clearly stated, would boil down to this multiple-choice question: Would you rather die of (a) oil wars, (b) climate change, (c) nuclear holocaust, or (d) all of the above? Or would you prefer the choice we're seldom offered: (e) *none* of the above? What if we could make energy do our work without working our undoing? Could we imagine fuel without fear? Could we…reinvent fire?

Fire made us human. Fossil fuels made us modern. But now we need a new fire that makes us safe, secure, healthy, and durable. That has now become possible. In fact, it works better and costs less than what we have been doing. Let's see how.

Four-fifths of the world's energy still comes from burning every year about 19 cubic kilometers of the rotted remains of primeval swamp goo, extracted and delivered with immense skill. Those fossil fuels have built our civilization, created our wealth, and enriched the lives of billions. But their rising costs to our security, economy, health, and environment are eroding if not outweighing their benefits—so we need a new fire.

Switching from the old fire to the new fire changes two big stories: oil and electricity. Each puts about two-fifths of the fossil carbon into the air, but they're quite distinct. Less than 1% of U.S. electricity comes from oil, *vs.* two-fifths from coal. Yet the *uses* are of oil and electricity similarly concentrated. Three-fourths of our oil fuels vehicles, three-fourths of our electricity runs buildings, and the rest of both runs factories. So very efficient transport, buildings, and factories can save oil and coal, as well as natural gas that can displace both.

Today's energy system is not only inefficient; it's also disconnected, aging, dirty, and insecure, so it needs refurbishment. But by 2050, it could become efficient, connected, and distributed, with elegantly frugal autos, factories and buildings all relying on a secure, modern, and resilient energy system. Thus we can eliminate our addiction to oil and coal by 2050 and use one-third less natural gas while switching to efficient use and renewable supplies.

By 2050, this transformed energy system, with tripled end-use efficiency and three-fourths-renewable supply, could cost five trillion U.S. dollars *less* in net present value than business-as-usual, assuming that carbon emissions and all other hidden or external costs are worth zero—a conservatively low estimate. Yet this cheaper energy system could support a 158% bigger U.S. economy—all without oil, coal, or for that matter nuclear energy.

Moreover, this transition needs no new inventions and no new national taxes, mandates, subsidies, or laws, avoiding Washington gridlock. To repeat: I'll describe *how the United States could get completely off oil and coal by 2050, five trillion dollars cheaper, with no Act of Congress, led by business for profit.*

We can use our most effective institutions—private enterprise, co-evolving with civil society, sped by military innovation—to go around our least effective institutions. And whether you care most about profits, jobs, and competitive advantage, or about national security, or about environmental stewardship, Creation care, climate protection, and public health, reinventing fire makes sense and makes money.

General Eisenhower reputedly said that expanding the boundaries of a tough problem makes it soluble by encompassing more options and more synergies. Thus *Reinventing Fire* integrates all four energy-using sectors—transport, buildings, industry, and electricity—drawing on RMI's decades of deep practical experience in each. We also integrate four kinds of innovation: not just the usual two—technology and public policy—but also two more powerful ones normally left out: *design* (the way we combine technologies) and *strategy* (new business models, new competitive strategies). These combinations yield far more than the sum of their parts, especially in creating deeply disruptive business opportunities.

THE FIRST BIG STORY (OIL) IN BRIEF

U.S. mobility fuel goes three-fifths to automobiles, so it's logical to start by making automobiles oil-free, then tripling the efficiency of heavy trucks and airplanes (which can improve roughly twofold more in the long run). We can then switch their fuels to any mix of hydrogen, electricity, and advanced biofuels. These shifts are summarized in my companion paper in this Symposium, "Oil-Free Transportation," so I won't repeat here their physics-based logic, their compelling economics, or the encouraging signs that they're gaining encouraging market traction. But in brief, *Reinventing Fire* found that with a $4-trillion lower net-present-value cost than business-as-usual counting no externalities (or $12 trillion including just the economic and military costs of U.S. oil dependence), the United States could provide far greater mobility in 2050 than today, but use no oil. Saving or displacing all its oil at less than one-fourth its 2014 world price would yield a 17% internal rate of return counting just private internal costs and benefits. In short, oil is becoming uncompetitive even at low prices *before* it becomes unavailable even at high prices. That's like what happened with whale oil in the 1850s, when whalers ran out of customers before they ran out of whales.

THE SECOND BIG STORY—ELECTRICITY

The electrified carbon-fiber and light-metal autos that are today's market harbingers of this shift beyond oil mustn't, and don't, merely rename the oil problem by adding new burdens to the electricity system. Rather, when smart autos exchange electricity and information through smart buildings with smart grids, they're adding to the grid distributed flexibility and storage that help the grid accept varying solar and windpower. Electrified autos thus make the auto and electricity problems easier to solve together than separately, and they converge the oil story with our second big story—saving electricity, then making it differently. These twin revolutions in electricity promise more numerous, diverse, and profound disruptions than in any other sector, as twenty-first-century technology and speed collide head-on with twentieth- and nineteenth-century institutions, rules, and cultures. Those disruptions are already widely recognized in the industry, causing a rapidly evolving mix of excitement and panic, and spawning such important institutional innovations for rapid learning as RMI's e$^-$Lab (Electricity Innovation Laboratory).[3]

As usual, the magic key is efficient use. Changing how we make electricity gets easier if we need less of it. Today, most of it is wasted. Efficiency techniques keep improving faster than they're applied, so the unbought reserves of "negawatts" (saved watts) keep getting bigger and cheaper. Yet as buildings (using three-fourths of the electricity) and industries (using one-fourth) start to get efficient faster than they grow, U.S. electricity use could start shrinking—its trend since 2007—despite the extra use for electric autos. Moreover, we can do this by reasonably accelerating existing efforts. The savings described next can be achieved by 2050 if national-average adoption of efficiency matches by 2030 the levels already achieved by 2005 in the Pacific Northwest states. Whatever exists is possible.

MULTIPLYING BUILDING EFFICIENCY

Reinventing Fire found that by 2050, U.S. buildings can triple or quadruple their 2010 energy productivity, saving $1.4 trillion net present value with a 33% internal rate of return (Figs. 1, 2). The savings are worth four times their cost. This doesn't count major forms of proven value *beyond* saved energy costs, such as higher productivity and better health in efficient offices, higher sales in efficient and well-daylit stores, faster healing and better clinical outcomes in efficient green hospitals, and many forms of increased real-estate value. Together these are often worth one, sometimes two, orders of magnitude more than the energy savings themselves.[4] Furthermore, RMI's field-tested "deep retrofit" techniques—optimizing whole buildings and doing the right improvements in the right order *at the right time*—can strikingly enhance returns and help manage risks in real-estate portfolios.[5] This approach is therefore spreading rapidly among real-estate professionals. Ref. 1's Chapter 3 offers extensive examples, and retrofitdepot.org presents an expanding toolkit used by many practitioners.

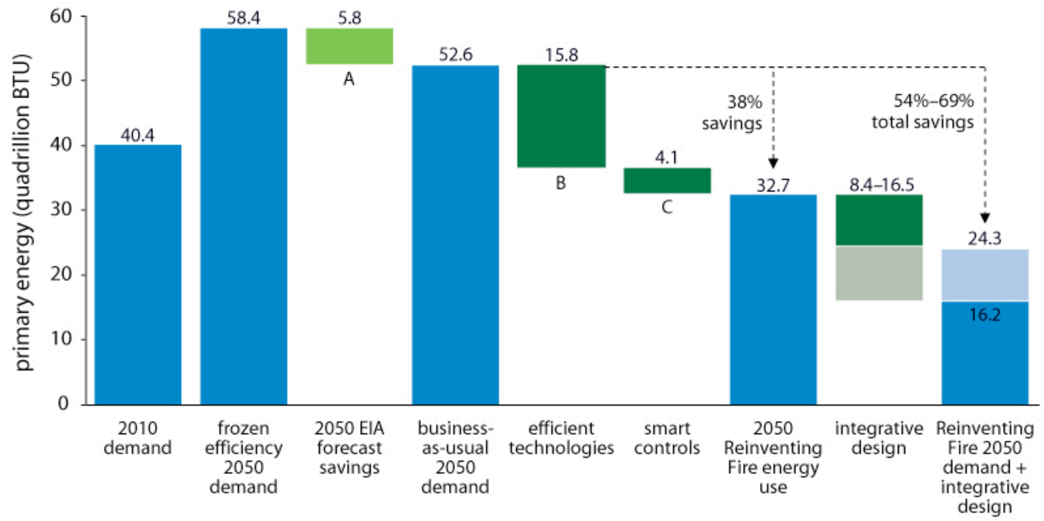

Fig. 1. The 54–69% energy-saving potential beyond government forecasts (A = Energy Information Administration January 2010 Reference Case), or 58–72% below 2050 demand at 2010 levels of efficiency. Efficiency gains B are taken from National Academy of Sciences analysis; smart controls (C) from an American Council for an Energy-Efficiency Economy metastudy; and a range of further integrative-design savings from a conservative assessment of numerous practical cases (see Fig. 2), assuming that this technique increases savings but doesn't also decrease their cost, as skilled practitioners often achieve too. This graph and Figs. 3, 4, and 10 were first published by Chelsea Green in ref. 1.

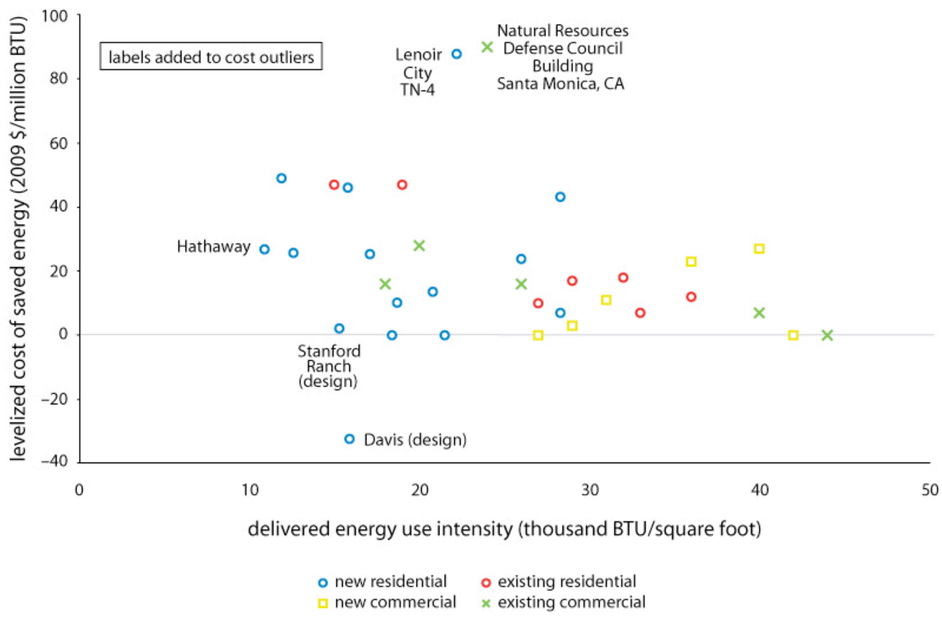

Fig. 2. Examples of RMI's integrative-design case-studies in four categories. Costs of saved energy vary widely, reflecting differences in design and execution quality, because few designers and builders are yet skilled in this approach. These differences make the outcome uncertain, but represent a major business opportunity in taking best practice rapidly to scale. RMI's analysis (ref. 1), rather than cherry-picking best cases, conservatively averaged mean savings in the upper and lower halves of each of the four data sets.

Applying historically reasonable retrofit rates to stock-and-flow assumptions consistent with official forecasts, *Reinventing Fire* found this plausible trajectory for U.S. buildings' primary energy use (Fig. 3):

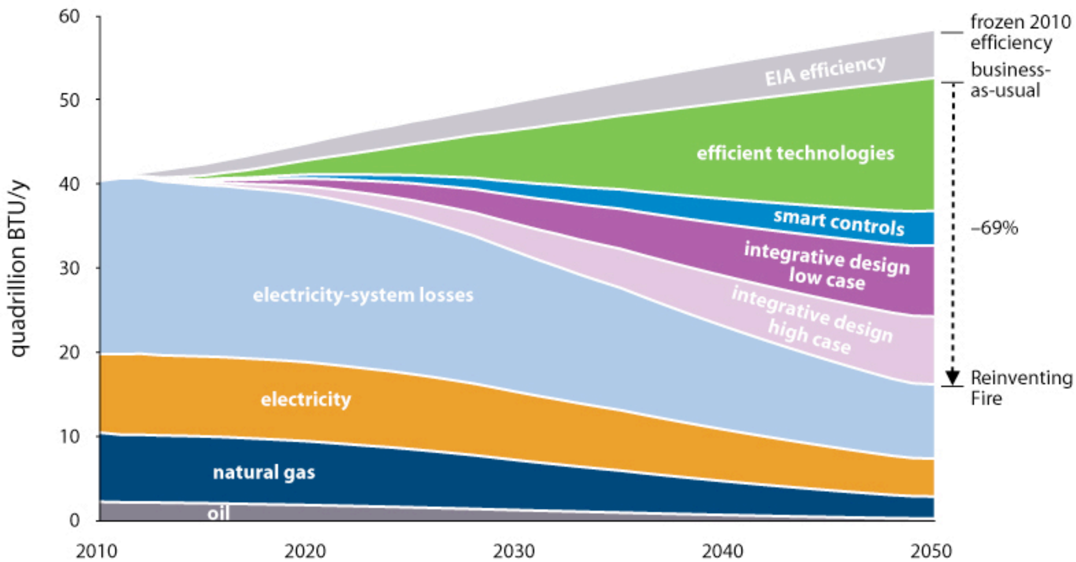

Fig. 3. Projected decline in U.S. buildings' primary energy use, combining conventional improvements with a range of integrative-design savings markedly inferior to what RMI's engagements normally achieve.

DOUBLING INDUSTRIAL EFFICIENCY

Similarly, *Reinventing Fire* found that U.S. industry—an enormously complex mix of interlinked activities—can double its energy productivity by 2050, averaging a 21% internal rate of return (Fig. 4):

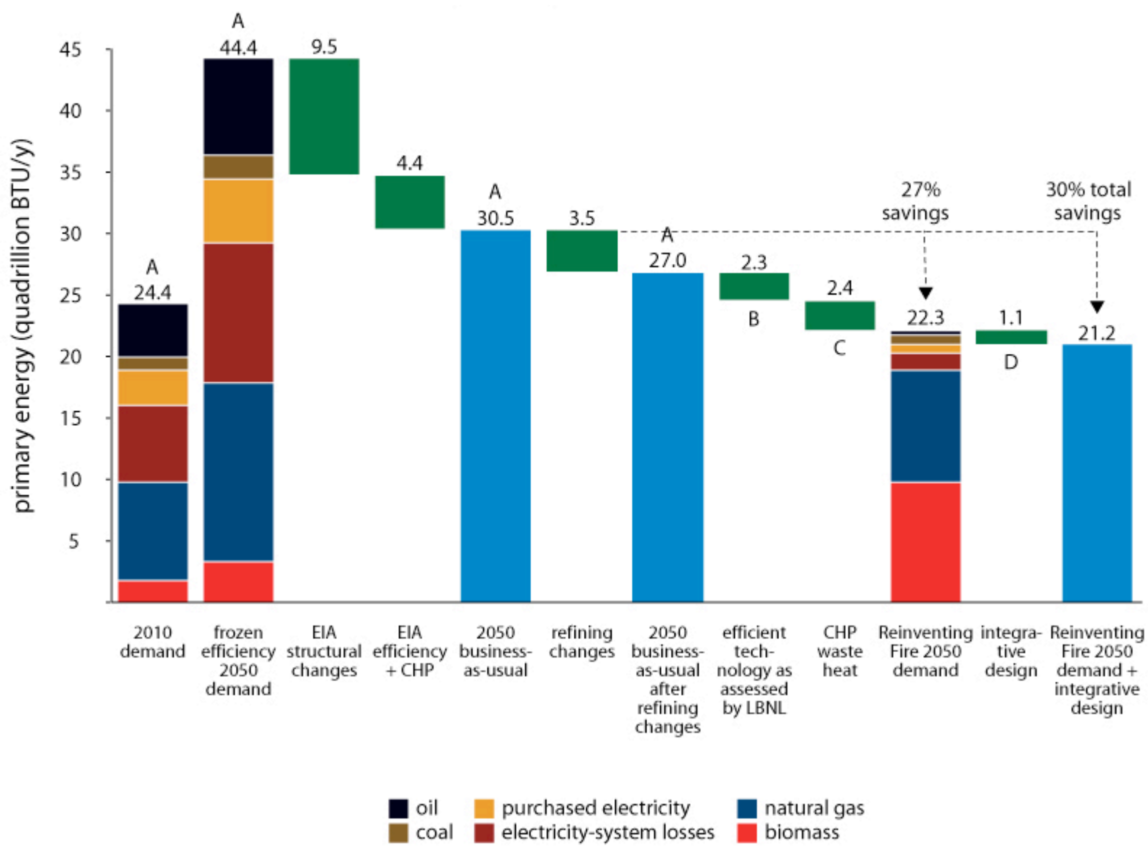

Fig. 4. Energy-saving potential in U.S. industry, 2010–2050. CHP means combined-heat-and power

(cogeneration). Savings from structural shifts, such as not needing to refine oil or produce steel that the transportation sector (and others) no longer need, are also shown, and are adjusted to reflect the energy needed to produce their substitutes. Item B adds newer technologies assessed in detail by Lawrence Berkeley National Laboratory in 2010. Item D conservatively accounts for otherwise omitted integrative-design savings only in fluid-handling and motor-drive systems, but not in industrial process improvements, where such savings are typically large but too heterogeneous to generalize from with confidence.

These steps can cut industrial energy use 27% below 2050 business-as-usual despite 84% higher output.

INTEGRATIVE DESIGN FOR BIGGER, CHEAPER SAVINGS

Making these savings even bigger is a disruptive innovation, long developed at RMI[6], called "Integrative Design." It is not a technology but a change in how technologies are applied and combined. It can often make very large energy cost *less* than small or no savings, yielding expanding returns, not diminishing returns.

That's how our retrofit two years ago is saving two-fifths of the energy in the Empire State Building. Remanufacturing its 6,514 double-glazed windows onsite into superwindows that let light through but block heat (and insulate four times better), plus better lights, office equipment, and the like, together cut the maximum cooling load by a third. Then renovating smaller chillers, instead of adding bigger ones, saved $17 million of capital cost, paying for most of the other improvements and cutting the payback time to just three years. The state of the art is moving so fast that another retrofit RMI just completed in a big old Denver office building is expected to save 70% of its energy cost-effectively.

Or consider a smaller building with a much higher surface-to-volume ratio. My wife Judy and I live high in the Rocky Mountains where pre-global-warming temperatures used to dip as low as –44C. This house has helped inspire more than 32,000 European "passive buildings" that, like ours, need no heating but have roughly normal construction costs. Indoors, our house is a passive-solar banana farm, wrapping around an 85-m^2 jungle that by spring 2014 had yielded 54 banana crops with no furnace (Fig. 5).

Fig. 5. The author's home, "passive-solar banana farm," and research center (originally RMI's headquarters 1982–2000) in Old Snowmass, Colorado, at 2200 m elevation near Aspen. The building wraps around the semitropical jungle (lower left); in spring 2014, seven banana crops were ripening simultaneously. The previous two (lower right), weighing 30 kg, harvested themselves by pulling down the tree a year earlier. (Photos courtesy of Judy Hill Lovins.)

In 1984, this house was saving about 99% of the usual space- and water-heating energy and 90% of the household electricity, all with a 10-month payback. Today's technologies, which we have lately retrofitted, are better—how much better, we'll know when we're through commissioning the measuring software. The trouble is that the measuring equipment seems to use more electricity than the lights and appliances.

This design approach works in any climate, including eliminating air conditioning up to 46˚C (not an upper bound) in central California with lower construction cost and better comfort, or saving 90% of air-conditioning energy in steamy Bangkok with normal construction cost and better comfort. (Nearly everyone in the world lives in a climate between those of Bangkok and Old Snowmass.) The key is integrative design that achieves multiple benefits from single expenditures. For example, the arch that holds up the middle of our house has twelve functions but only one cost.

Integrative design can also increase the half-trillion dollars of conventional energy savings in industry. Dow is already capturing $9 billion of those savings on a $1-billion investment, and the profit is still growing. But there's more to do. For example, three-fifths of the world's electricity runs motors. Half of that runs pumps and fans. All of those devices can be improved, and the motors that turn them can save about half their energy by integrating 35 improvements that can together pay back in about a year.[7] First, however, we should capture bigger, cheaper savings that are normally ignored, not yet in the engineering textbooks, and not yet in any official study.[8]

For example, pumps, the biggest use of motors, move liquid through pipes. A typical industrial pumping loop, though, was redesigned to use at least 86% less pumping energy. This was achieved not by getting better pumps, motors, or controls, but by replacing long, thin, crooked *pipes* with fat, short, straight pipes.[6] That also shrinks the pumping equipment and its capital cost. This isn't new technology; it's re-arranging our mental furniture as designers, so we choose big pipes and small pumps—not the opposite—and lay out the pipes first, then the equipment—not the reverse.

What do such savings mean for the three-fifths of our electricity that's used in motors? Of the coal burned at the power plant, the many compounding losses in the power plant and the pumping system lose 90%, so only 10% of that initial fuel energy comes out the pipe as flow (Fig. 6). But if we turn those compounding losses around backwards into compounding *savings*, each unit of flow or friction saved in the pipe compounds back to save *ten* units of fuel, costs, pollution, and climate change back at the power plant. And as you go back upstream, the components get smaller and cheaper, so the total capital cost decreases.

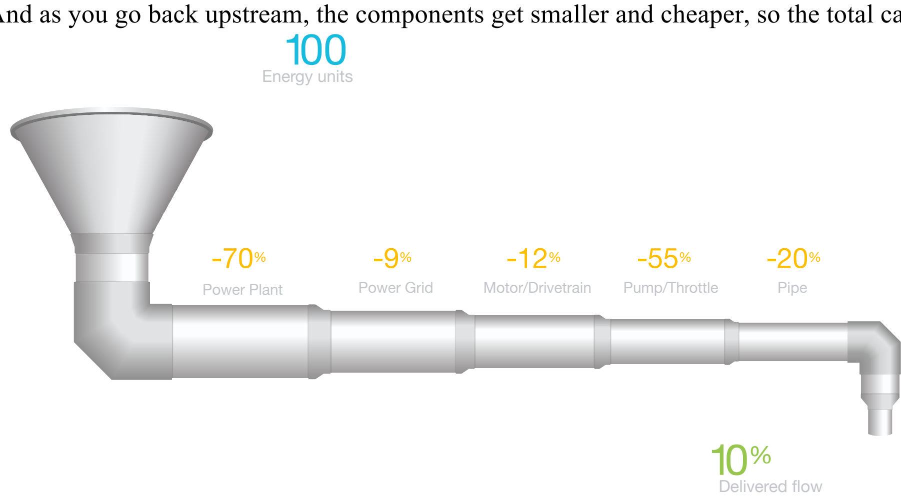

Fig. 6. Compounding losses lose ~90% of the fuel energy fed into a standard thermal power plant before emerging from a pumping system as flow. Conversely, each unit of flow or friction saved in the piping system compounds backwards from right to left, saving ten units of fuel at the power plant. This illustrates why savings should always start downstream.

RMI's consulting team has lately found such snowballing energy savings in over $40 billion worth of industrial redesigns ranging from data centers and microchip fabrication plants to mines and refineries. Typically our retrofit designs save about 30–60% of the energy with a 2–3-y payback, while our new-facility designs save about 40–90% with generally *lower* capital cost.

A schematic illustration from a data-center project for EDS (now HP) shows the logic of starting the savings downstream (Fig. 7).

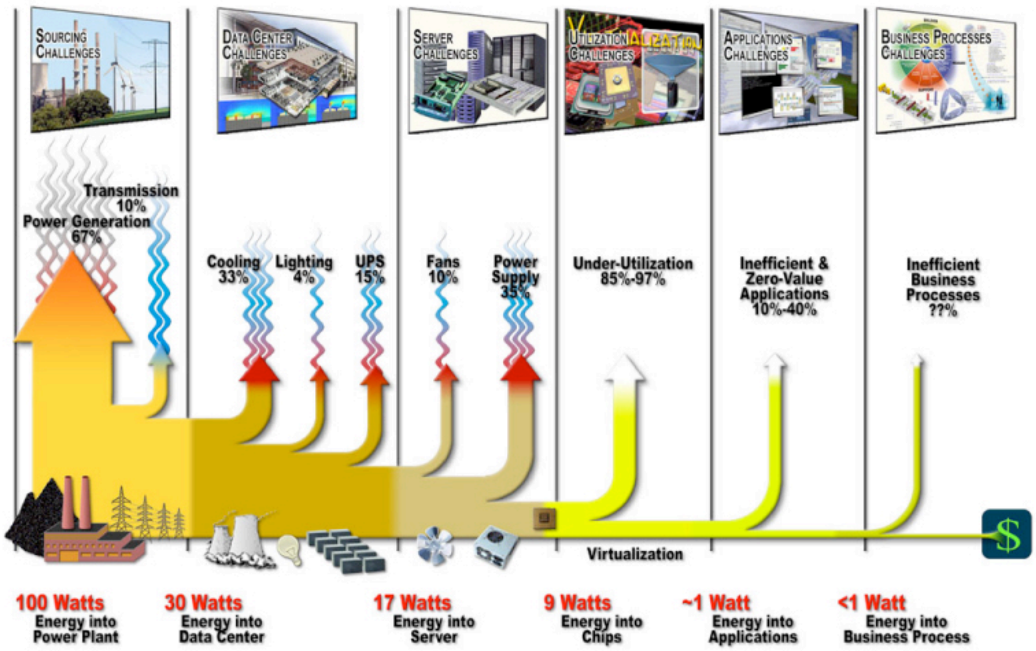

Fig. 7. Compounding losses often totaling 4–5 orders of magnitude from power-plant fuel to delivered customer value (left to right) offer enormous savings when run backwards, starting at the right. Replacing bloatware with terse code elegantly compiled, so every compute cycle is a needed and wanted one, can save up to two orders of magnitude on computing per unit of service; virtualization (combining less-used applications onto a single physical server), up to one order of magnitude; better servers, more than fourfold; then an order of magnitude less power supply and cooling is needed, and these services can be delivered far more efficiently; and finally, fuel-cell trigeneration could halve the utility losses. Altogether, these potential savings can multiply to at least two orders of magnitude, with much lower capital cost.

THE ELECTRICITY SUPPLY REVOLUTION

Needing less electricity would ease and speed the shift to new ways of producing it, chiefly renewables. China leads their explosive growth and plummeting cost. Solar and windpower are marketplace winners today. In many parts of the U.S. their levelized power cost already beats that of new combined-cycle gas-fired plants, even though renewables' temporary subsidies are typically less than those permanently provided to nonrenewables. The global clean energy sector invested in 2011 its trillionth dollar since 2004, helping to build our next economy. America now has more solar workers than coal or steel workers, and those solar jobs are growing ten times faster than general employment.

Already in about 20 states throughout America, private installers can put photovoltaic panels on your roof with no money down (soon with cash back) and beat your electric bill. Such unregulated products can ultimately add up to a "virtual utility" that bypasses the electricity company even more than wireless telephones bypassed the wireline phone companies. Of the 10–15% of Hawai'ian households already using rooftop solar power to escape costly oil-fired utility power, many have even found it worthwhile to add enough battery storage to drop off the grid altogether. That option will become viable across the United States well within the lives of existing utility assets, leaving old business models no place to hide.[9] This prospect gives utility executives nightmares and venture capitalists sweet dreams.

Such competition is already very large. Half of the world's new generating capacity added each year starting in 2008 has been renewable (including big hydro dams), the majority lately in developing countries. But mass-produced, modular renewables are rapidly taking over the market. Solar power is scaling faster than cellphones. In 2012 , two-thirds of Europe's new capacity was solar and windpower, and the world had the capacity to make fifty billion watts of solar cells. In 2013, some new U.S. solar plants sold their power for under a nickel a kilowatt-hour, while the best windfarms' power price neared a once-unimaginable two cents. Without their temporary Federal tax credits (already expired for wind projects not begun in 2013, and expiring for solar in 2016), these prices would respectively be around 7 and 4¢/kWh, undercutting all new and some existing fossil-fueled and nuclear plants—especially as solar projects adopt the radical installation streamlining already achieved in Germany and Australia. Most of the solar system cost is now for installation, not hardware, so in 2013, Solar City's module price ticked up 3% but its installed system cost fell 30%. Renewables are getting inexorably cheaper while fossil and nuclear power get inexorably costlier. Wherever the cost curves haven't yet crossed, they soon will, making even solar power grid-competitive in most of the world over the next *few years*, sooner than a new fossil-fueled or nuclear plant could even be built.

In each of the past three years worldwide, renewables *excluding* big hydropower have received a quarter-trillion dollars of private investment and added over 80 billion watts. They now far surpass the total global installed capacity, and sometime in 2014 they will probably surpass the electrical output, of nuclear power, whose dwindling annual net additions turned negative even before Fukushima. Global orders for nuclear and coal plants continue to fade away because they cost too much and have too much financial risk to attract investors.

After eight years of U.S. 100+% construction subsidies offered to new nuclear plants, not one of 34+ proposed units was able to raise private construction capital, because they have no business case. About 90% of them got shelved; the surviving few are all funded by conscripted customer and taxpayer capital. This market collapse is good news for climate protection, since new nuclear build is so costly and slow that it would reduce and retard carbon savings by saving far less carbon per dollar or per year than investing instead in efficiency, renewables, or cogeneration.[10]

Yet without new nuclear plants, how could the U.S. displace its hundreds of coal-fired power plants? Efficiency can displace them roughly twice over at probably less than their operating cost. Efficiency plus gas or modern renewables or both can displace them much sooner, and ultimately more than 23 times over, at less than their replacement cost. But we need replace them just once. Indeed, during 2005–13, coal lost 21% of U.S. electricity market share, and now faces stiff challenges across Asia. Forty-two billion watts of planned coal capacity were shelved in India in 2012 alone, and India's new government is strongly pro-renewable. China in 2012 got more electricity from windpower than from nuclear power, and added more generation from non-hydro renewables than from all fossil and nuclear sources combined. In 2013, China added more solar capacity than the U.S. has, and raised its 2017 target to 70 billion watts.

We're often told, though, that only coal and nuclear plants can keep the lights on, because they're "24/7," while photovoltaics and wind are variable and hence supposedly unreliable. In fact, no generator is 24/7; they all break. U.S. coal and nuclear plants are typically down about 10–12% of the time. And when a big thermal power station shuts down, the grid typically loses a billion watts in milliseconds, often for weeks or months, sometimes without warning.

That's why for over a century the grid has been built to handle this intermittence by routinely substituting working plants for failed plants. In exactly the same way, grids can handle the predictable variations of photovoltaics and windpower, both of which can be forecasted at least as accurately as demand. Indeed, largely or wholly renewable grids can deliver highly reliable power when they are forecasted, integrated, and diversified by both type and location: variable renewables can be backed up by renewables in other places, or of other kinds, or both. Thus the National Renewable Energy Lab published a detailed analysis of reliable and economically attractive 80–90% renewable electricity for the whole United States[11], and the European Climate Foundation did the same for Europe.[12] But this is also true for smaller and harder areas like Texas, whose grid is isolated from the rest of the United States.

The Texas power pool's loadshape for a summer week in 2050 can get smaller and less peaky by adopting what the National Academy of Sciences considers very profitable efficiency, but it still needs over 30 billion watts. Adding enough windpower and photovoltaics to meet 86% of the annual electricity need doesn't produce a great match to the loadshape. But getting the other 14% from dispatchable renewables (those you can use whenever desired), like geothermal, small hydro, solar thermal electric, and biogas, makes the supply 100% renewable. It can then be further matched to the load by using surplus electricity for ice-storage air conditioning and smart charging of electrified autos, recovering that distributed storage when needed, and filling the last gaps with unobtrusively flexible demand. Then all the moving parts fit together to provide reliable electricity every hour of the year without adding bulk storage.[13]

Some utilities are already choreographing variable renewables in this way. In 2013, Germany got 25% of its electrical consumption from renewables, Spain 45%, Scotland 46%, Denmark at least 47%, and Portugal 58%. Without adding bulk electricity storage, all five countries delivered reliable electricity; Denmark and Germany had the most reliable power in Europe, an order of magnitude more reliable than America's. Such European experience supports a transition over decades to largely or wholly renewable electricity for the entire European Union. A major lesson from Europe is that the challenges of mostly renewable supply come much less from variable renewables themselves than from trying to *combine* them with inflexible "baseload" plants—which, fortunately, are retiring as they become uncompetitive.

In America today, our aging, dirty, and insecure electricity system must be replaced by 2050. Whatever we replace it with is going to cost about $6 trillion net present value, whether we buy more of what we've got, or new nuclear and "clean coal," or centralized renewables, or more-distributed renewables. These scenarios, whose demand trajectories are shown in Fig. 8, have virtually identical costs, but differ profoundly in their *risks* around national security, fuel, water, finance, technology, climate, and health. Water use alone is three times greater for the upper two than the lower two scenarios.

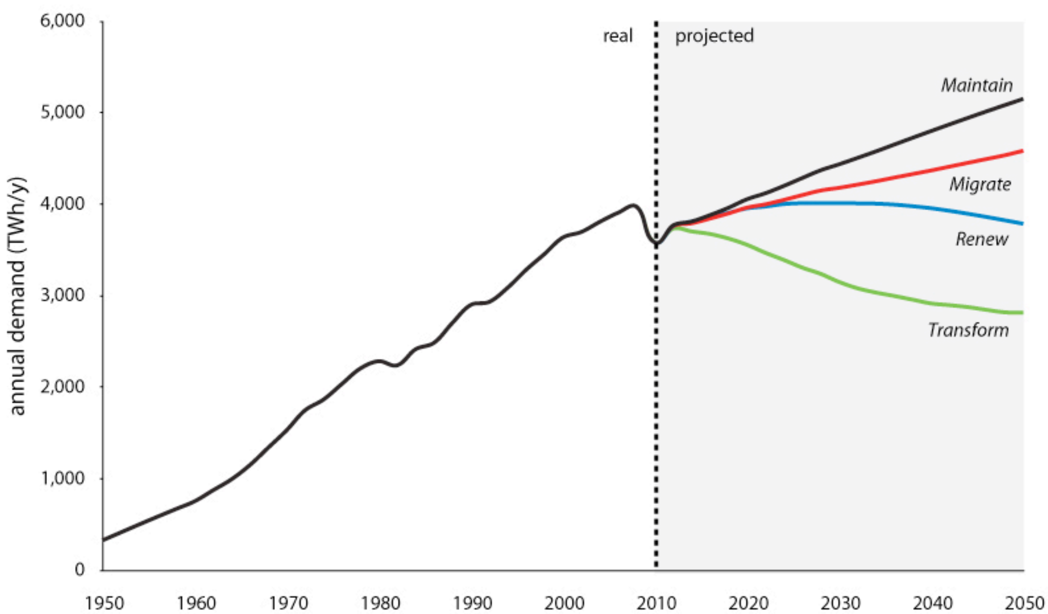

Fig. 8. The demand trajectories logically corresponding to ref. 1's four U.S. electricity scenarios: Maintain *(business-as-usual),* Migrate *(new nuclear build and "clean coal"),* Renew *(centralized renewables), and* Transform *(half-centralized and half-distributed renewables).*

The starkest contrast is in national security. The overcentralized U.S. grid is especially vulnerable to cascading and potentially economy-shattering blackouts caused by bad space weather, bad earth weather, earthquakes, or cyber- and physical attack. Yet that blackout risk disappears, and all six of the other risks are best managed, with distributed renewables organized in local "microgrids" that normally interconnect but can stand alone at need: they can disconnect fractally and reconnect seamlessly, just as our house does.

That's where the Pentagon is headed with its bases' power supply, because they need their stuff to work—but so do the rest of us whom they're defending. Pursued nationwide, at about the same cost as business-as-usual, this resilient grid architecture would maximize not just national security but also customer choice, entrepreneurial opportunity, and innovation.

Together, efficient use and diverse, dispersed, renewable supply are starting to transform the whole electricity sector. Traditionally, utilities built giant coal, nuclear, and gas-fired plants and maybe a little efficiency and renewables. Those utilities were rewarded, as they still are in 36 of the United States, for selling you more electricity. But now, especially where regulators instead reward cutting your *bill*, the market is shifting massively towards efficiency, renewables, combined heat and power, smart grids, and ways to blend them all together reliably with less transmission and little or no bulk electricity storage.

So our energy future is not fate but choice, and that choice can be very flexibly exercised (Fig. 9):

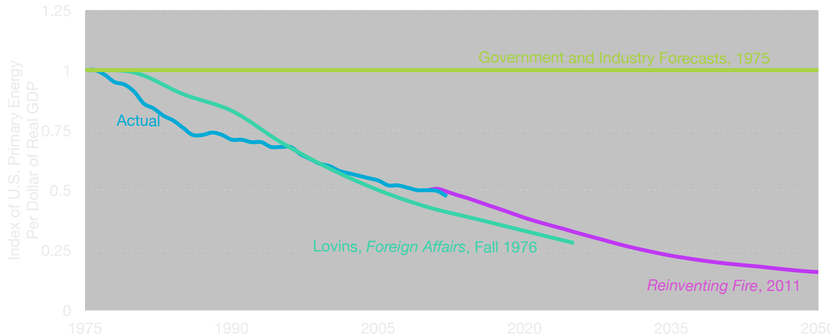

Fig. 9. In 1976, the U.S. government and industry all said the amount of energy needed to make a dollar of real GDP could never fall. My 1976 article in Foreign Affairs *heretically suggested that this energy intensity could drop by severalfold. So far, it's fallen by more than half. Yet today's more powerful technologies, more streamlined and mature delivery, marketing, and financing channels, and integrative design can together triple efficiency all over again at about one-third the ~1980 real cost.* ***[Rob, we'll re-do this graph to make its light-gray axis labels readable and remove the gray block.]***

To solve the energy problem, we just needed to *enlarge* and *integrate* it. The results may at first seem incredible, but as Marshall McLuhan said: "Only puny secrets need protection. Big discoveries are protected by public incredulity."

Now combine the electricity and oil revolutions, and you have the really big story of *Reinventing Fire* (Fig. 10), where business, enabled and sped by smart policies in mindful markets, could lead the U.S. (for starters) completely off oil, coal, and nuclear power by 2050, holding the share of natural gas constant at 24% but reducing its amount by a third, quintupling renewables, tripling efficiency, and using vehicles more productively. All this could save $5 trillion net present value, grow the economy 2.58-fold, strengthen national security, and by eliminating oil and coal, and cut fossil carbon emissions by 82–86%. If you like any one or more of those outcomes, you can support *Reinventing Fire*—without needing to like every outcome, and without needing to agree which outcome is most important. Focusing on outcomes, not motives, can turn gridlock and conflict into a unifying solution to our common energy challenge.

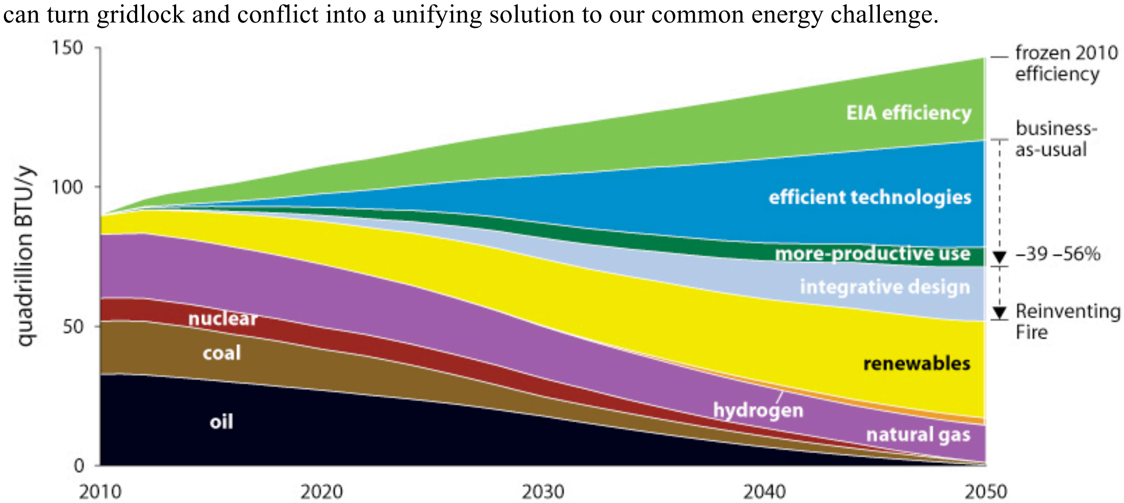

Fig. 10. The total U.S. primary energy use, 2010–50, synthesized in ref. 1: tripled efficiency, plus renewables raised from a tenth to three-fourths of total supply, displace the costlier sources that now supply 90% of U.S. primary energy. The estimate shown for 2050 natural-gas use is probably conservatively high, since RMI assumed cogeneration only in industry, not also in buildings, and didn't assume any solar process heat even though some is cost-effective today.

Even without carbon pricing and despite a cold winter and a 6% larger real GDP, U.S. carbon emissions in 2013 were 10% below their peak in 2007. In the next decade, that drop could expand to 20–

30% due to durable trends in supply and demand that are already well underway. These best buys also happen to be the most effective solutions to global problems that hazard everyone's security and prosperity. So our team at Rocky Mountain Institute is rapidly expanding its efforts to help smart companies get unstuck and speed this journey via many sectoral initiatives and projects, with more hatching.

Of course, there's still a lot of old thinking around too: as former oilman Maurice Strong said, "Not all the fossils are in the fuel." But DuPont's former chairman, Edgar Woolard, reminds us that "Firms hampered by old thinking won't be a problem, because they simply won't be around long-term."

What I've described to you is not just a once-in-a-civilization business opportunity; it's one of the greatest transformations in the history of our species. We humans are really inventing a new fire—not dug from below but flowing from above. (I've even heard theologians talk about energy from hell and energy from heaven.) The new fire is not scarce but bountiful; not local but everywhere; not transient but permanent; not costly but free. And but for the transitional tail of natural gas and a little biofuel, grown in ways that sustain and endure, this new fire is flameless. Efficiently used, it really could make energy do our work without working our undoing.

Each of you owns a piece of that $5-trillion prize. *Reinventing Fire* details how you can capture that opportunity. So let me invite you to engage with us, with each other, and with everyone around you to help make the world healthier, richer, fairer, cooler, and safer by together reinventing fire.

ACKNOWLEDGMENTS

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