About *Reinventing Fire* and this website

This technical website supports, elaborates, and documents the book *Reinventing Fire*, published in autumn 2011 by Chelsea Green (www.chelseagreen.com) for Rocky Mountain Institute (www.rmi.org) and available at www.reinventingfire.com. *Reinventing Fire* provides a roadmap for shifting the United States' energy system completely from oil and coal to efficiency and renewables by 2050 (and later eliminating the residual "tail" of natural-gas use), at a $5-trillion lower net-present-value cost than business-as-usual (excluding all hidden costs), requiring no new inventions or Acts of Congress, led by business for profit.

This site is organized by hyperlinks to the Executive Summary. Its six chapters also have their own executive summaries: integration (Chapters 1 and 6), transportation (Chapter 2), buildings (Chapter 3), industry (Chapter 4), and electricity (Chapter 5).

This site is meant to supplement, complement, and document, and to a limited degree to summarize, the book Reinventing Fire*—but not to replace it*. Most of the book's content cannot be found on this site, so you are invited to read the book first. We do not recommend that you try to absorb its content only by perusing this site; that will miss many of its key themes and findings. Here's a quick guide to *Reinventing Fire*'s intent, features, and methodologies:

Audience and level. In the United States as in many societies, the most dynamic force, the most effective way to get big things done quickly, is typically the private sector in its coevolution with civil society. In most societies, especially at a national level, government is gridlocked or overtaken by events, so public policy often lags behind market actors. Because *Reinventing Fire* describes an immense challenge and opportunity—where action is imperative, failure can be grave, and the race is to the quick—it addresses mainly the leaders of our most effective institutions: business and the military. Such people are busy, so *Reinventing Fire* is relatively brief and terse.

Detail. The subject is complex, so without sacrificing accuracy, *Reinventing Fire* is simplified to make it accessible to ordinary educated readers with no special technical background. Nearly all the previous 30 books by *Reinventing Fire*'s senior author were heavily documented, as if his favorite unit of measure were "footnotes per furlong." RMI's most recent book on this subject had 333 dense pages with ten color-coded text formats, 987 notes, and nearly a thousand references. In contrast, *Reinventing Fire*, despite its wider scope and even deeper analytic base, has fewer notes and references, and they're all at the back rather than cluttering the text. This website's Knowledge Center, and its and the book's notes and citations, fill in most of the technical details; any others required are available on request. Rocky Mountain Institute is committed to the transparency and scrutability of the very detailed analysis behind *Reinventing Fire*—a more than $5-million research effort with extensive industry support, as summarized in the book's Acknowledgements on pp 252–257. The myriad sources that document its findings, the scores of spreadsheets and hundreds of graphs that detail its calculations, and the extensive technical analyses that support its conclusions are summarized free on this website. Researchers needing fuller access to these technical supporting materials should kindly contact the research team at rf@rmi.org.

Scope and limitations. The book *Reinventing Fire* summarizes a "grand synthesis" of a detailed roadmap for getting the United States completely off oil and coal by 2050 (and natural gas somewhat later), led by business for profit. It is a versatile and flexible framework for understanding opportunities, not a dogmatic revealed truth, because the future is unknowable: as President Eisenhower said, "Plans are worthless, but planning is everything." It presents such information, and no more, as is needed to convey a sound grasp of the subject from an independent perspective. The book and this website offer an informed view based on rigorous analysis and deep practical experience transparently presented, but they cannot present a consensus where none exists, and do not purport to represent every perspective or anticipate every objection. We emphasize U.S. conditions within a global context, with special reference to China and India, but don't pretend to global completeness. *Reinventing Fire* focuses on energy solutions and outlines their main links to economy, security, global development, and environment, but it's not mainly about those tangential topics. Nor does it try to solve or even identify every societal ill, wrong, or issue. Solving the energy problem is necessary but not sufficient for solving all problems, let alone alleviating all suffering in the universe. Our goals are more modest.

Distinctiveness. Fourteen main features distinguish *Reinventing Fire* and this website from others about the new energy agenda. Our treatment is about solutions, not problems, and practice, not theory. We address mainly business leaders, not policymakers, because the outcomes we present are driven by private profit more than by public policy, and by competitive risk and reward, not by carbon pricing. Our underlying analysis is rigorous, deep, and documented, not journalistic and anecdotal. Its logic is holistic and integrative, not narrow and reductionist. It emphasizes demand more than supply. It asks what is the right size and scale for the task. Its stance is independent, not biased toward favored fuels or technologies, and its content is cutting-edge (updated to August 2011), not conventional-wisdom. Our synthesis explains not just what to do but also how. It melds military with civilian opportunities. It's transformational, not incremental; audacious, not meek. It's attractive across diverse ideologies and goals, no matter whether you care most about security, jobs and profits, or climate and environment. It is offered in a spirit not of gloom but of applied hope.

Integration. *Reinventing Fire*'s unusual integration across all four energy-using sectors—transportation, buildings, industry, and electricity generation—and four forms of innovation—in technology, design, policy, and strategy—follows advice widely attributed to General Eisenhower: "If a problem cannot be solved, enlarge it."[i] That is, if you can't solve a problem, that's probably not because it isn't small enough to be bite-sized, but more likely because its boundary isn't large enough to encompass the options, synergies, and degrees of freedom that its solution requires. Solving, for example, the automobile and electricity problems is far easier together than separately.

Conservatisms. We assume only technologies already in or entering the market—visibly in the commercialization pipeline—and thus probably greatly understate future opportunities. We uncritically assume government projections that by 2050, Americans will drive 90% more, truck 118% more, fly 61% more, use 70% more floorspace, produce 84% more manufactures, and generate 2.58 times more Gross Domestic Product than they did in 2010—all with no constraints caused by *e.g.* investment, land-use, road and air traffic congestion, personal time budgets, inequities, social tensions, or dissatisfaction. We omit many energy-saving options that are individually small but collectively large. That is, beyond any changes in lifestyles implicit in those enthusiastic official growth forecasts, we assume no others that could materially reduce convenience. Similarly, we assume only ways to influence the timing of electricity uses unobtrusively to customers, entailing no discomfort or nuisance. Our analysis also contains specific technical conservatisms—for example, the lack of assumed cogeneration in buildings (Chapter 3) and of solar process heat in industry (Chapter 4), both of which tend to overstate 2050 needs for natural gas (Chapter 6).

Transparency. When modeling long-term energy transitions, less is more: it's better to be approximately right than precisely wrong, and simplicity and transparency trump complexity and opacity. Our calculations can be reproduced on a spreadsheet or a hand calculator; we don't rely on opaque or proprietary models. Our models and assumptions can be made available to bona fide technical researchers by arrangement via rf@rmi.org. Readers are also kindly invited to write reinventingfirecorrections@rmi.org with any clarifications, corrections, and suggestions. A log of any errors found and corrected in each printing is posted at errorlog.reinventingfire.com.

About the analytic methodologies in *Reinventing Fire*

Base case. All future scenarios are compared with our base case—the Reference Case that the U.S. Energy Information Administration (EIA), an independent government agency (www.eia.doe.gov), published in its January 2010 *Energy Outlook* and in its corresponding inputs to EIA's National Energy Modeling System (NEMS). (Where statistical lags required or EIA data were lacking, we used 2008 or 2009 data from other official or industry sources.) EIA's 2010 forecasts stop in 2035, so we extrapolate them linearly to 2050—based on historical experience, a good approximation. We didn't run EIA's NEMS model or other econometric forecasting models, because they're all unsuited to long-term projections, and all assume many parameters and model structures that our proposals aim to transform. Rather, we used the NEMS *inputs* to ensure that we've assumed the same economic growth and activity levels as EIA (such as travel, automotive size and performance, floorspace, comfort levels, etc.), so our different outcomes would be due solely to different energy efficiency and supply patterns. We also used EIA's NEMS inputs to make sure we didn't double-count efficiency gains that are already baked into our base-case forecast.

Future energy prices. We often test cost-effectiveness against EIA's energy price projections for 2035, extrapolated to 2050; those are not market price forecasts nor expected values, but rather reflect what EIA considered "normal" conditions consistent with its base-case demand assumptions. Neither we nor anyone else, we believe, has a sound method for forecasting long-term energy prices—especially under changes as strong, prolonged, and pervasive as this book suggests. EIA's track record with, say, oil-price forecasts is unimpressive[ii], but at least they are official, published, and consistent with base-case demand. As George E.P. Box remarked, "All models are wrong, but some are useful."

Deployment or adoption rates. We track rates of uptake for technologies and savings using historically grounded stock-and-flow models for each sector, consistent with NEMS results. We never assume that instant deployment is actually achievable. Sometimes we ask how much energy could be saved if, hypothetically, a given efficiency potential could be achieved fully and immediately—in order to distinguish it from how much energy could be saved under realistic deployment rates subject to constraints of stock turnover, training and startup lags, etc. Then we analyze how those constraints can be reduced by new business strategies or public policies. We actually assume that deployment rates demonstrated in particular places can be achieved, on average, nationwide over decades.

Behavioral and compositional changes. We separately quantify energy savings achieved by better technology and by its smarter use, so readers can understand both their separate and their combined effects. Similarly, we distinguish energy saved in industrial processes from ways to provide the same services from a smaller flow of materials and manufactured goods, such as designing products to use less material for longer. The latter option, though a durable trend, is scarcely assumed in our analysis.

Price re-equilibration. Our economic methods and principles are orthodox and generally neoclassical, but for convincing reasons described on page 35 of *Winning the Oil Endgame* (www.oilendgame.com, 2004), we didn't perform a general-equilibrium simulation to test how far our efficiency improvements would reduce energy prices, hence reduce efficiency's adoption. This is for seven main reasons: (1) within what the market will bear, oil prices are largely set by the OPEC cartel and influenced by its key members' cashflow requirements, (2) oil prices are certainly influenced by normal supply/demand considerations, but in a global market of which the U.S. is only one-fifth, (3) most of the marginal market is in countries like China and India, whose potential demand is huge and whose adoption of our approach would be wonderful but is far from guaranteed, (4) we don't think the market has fully priced in the prospects of geological depletion and geopolitical concentration and instability, (5) retail refined-product prices contain a substantial fixed-cost component that dilutes drops in crude-oil price, (6) sensitivity tests show that our superefficient electrified autos still pay back in three years in 2050 even if gasoline drops to $0.76 a gallon, and (7) if oil ever did get too cheap, which would be a nice problem to have, it could be taxed. We are also confident that reequilibrated prices would only slightly affect our findings. For example, the International Energy Agency's *2010 Annual Energy Outlook* contains a "450 Scenario" that saves 17% of base-case energy, yet estimates that 2035 world oil price falls from $135/bbl only to $90/bbl, still many times the cost of our savings: for example, all the oil savings and displacements (except biofuel provision) that completely decouple 2050 U.S. mobility from oil cost an average of less than $18 per saved barrel. Similar considerations apply to reequilibration of natural-gas prices.

Empiricism and precision. Focusing our analytic effort chiefly on big terms, we rely mainly on authoritative industry, government, and academic studies that are adequate, sound, available, and documented. Wherever possible, being empiricists, we use actual measurements, not theoretical projections. We also strive to avoid spurious precision, following Aristotle's counsel that "it is a mark of educated people, and a proof of their culture, that in solving any problem, they seek only so much precision as its nature permits or its solution requires."[iii]

Conventions of a dozen kinds are tedious—nontechnical readers can skip them—but for expert readers, the following 13 are necessary for avoiding opacity and confusion:

Money. All monetary amounts are expressed in 2009 U.S. dollars (unless otherwise noted) and deflated using the GDP Implicit Price Deflator. All present and future values and all levelized cost streams apply a 3% annual real discount rate—the societal rate specified for long-term federal energy-saving projects by the U.S. Office of Management and Budget—unless otherwise stated, as in our use of implicit consumer discount rates in buying autos. Prices exclude sales and ownership taxes on vehicles and all taxes on retail fuels, because those taxes are transfer payments, not real resource costs. As stated in *Reinventing Fire*'s note on p. x, "About This Book," our analysis screens efficiency investments against a 15%/y real hurdle rate in trucking, 3%/y for airplanes, 12%/y in industry, 7%/y in buildings, and 5.7% in electric utilities, and applies a three-year simple-payback horizon to new automobiles. We believe these investment criteria reasonably reflect the prevalent and typical norms in each sector. The Internal Rates of Return we calculate average 33% in buildings, 21% in industry, 17% in transportation, and 14% overall (including making the electricity system resilient and 80% renewable).

Physical units. Writing mainly for readers in the United States, which is moving toward the metric system inch by inch, we use customary U.S. units; foreign translations of *Reinventing Fire* will use international (metric) units for the convenience of readers from countries other than the U.S., Liberia, and Myanmar. Year is abbreviated "y," day "d," hour "h," second "s." Tons (t) are U.S. short tons (2,000 lb); metric tonnes (T) are 1,000 kg or ~2,204 lb. Thousand (10^3) is "k," million (10^6) is "M," billion (10^9) is a suffix "b" or prefix "G."

Light-duty vehicle efficiencies. Unless otherwise stated, we measure fuel economy using the "adjusted" USEPA combined city/highway driving cycle's miles per gallon. That's the figure used for sales stickers, but is 10% (city) or 22% (highway) below the "laboratory" mpg measured in EPA testing and used for Corporate Average Fuel Economy (CAFE) regulation. EIA converts rated efficiencies to actual oil use or savings by applying EPA's "degradation factor" to obtain actual "on-road" mpg, which we use in our automotive consumer adoption model. Fuel intensity is measured in gal/mi or L/100 km; to convert mpg to L/100 km or vice versa, divide into 235.2. Light-duty vehicle weights are curb weights unless otherwise stated.

Energy content. We use industry-standard conversion constants, and use the hydrocarbon energy content values in Appendix A of EIA's 2009 *Annual Energy Review*. We express fuels' energy content at their Higher Heating Value (which includes the energy needed to evaporate water created by combustion) except for hydrogen, where we use the 120 MJ/kg Lower Heating Value (which doesn't). We count the energy content of a kWh of electricity as 3,413 BTU (3.6 MJ), and where necessary, adopt the appropriate average heat rate reported by EIA in the 2009 *Annual Energy Review*. (This and all other EIA publications are posted at www.eia.doe.gov.) Unless otherwise stated, we measure electricity and its cost or price at the customer's retail meter rather than at the "busbar" (the generator's output terminals) for proper comparison between remote and onsite resources.

Hydrocarbon definitions. As in EIA usage, "petroleum" is crude oil plus lease condensate plus natural gas plant liquids, so liquefied petroleum gas (LPG) is "petroleum" whether it came from producing oil or natural gas. "Oil" may refer to crude oil or refined petroleum products or both, according to context. Since this book is about getting off fossil *fuel*—implying combustion—*it does not include feedstocks* **(use of fossil hydrocarbons as a raw material for chemical production rather than as a fuel)**. Feedstocks and their displacement by various efficiencies and substitutions are briefly discussed in Chapter 4.

Petroleum processing. U.S. government statistics measure oil by volume (1 barrel = 1 bbl = 42 U.S. gallons = 159 L), but refining heavy crude oil into lighter refined products expands its volume while consuming energy and money. We therefore convert from saved end-use fuel back to avoided refinery inputs of crude oil not by relative volume but by using their EIA-compiled relative energy content as the best measure of utility. (We don't adjust that conversion for refineries' energy use because that's included in industrial energy consumption.) Rather than using complex calculations to convert the cost of saved fuel back to Refiners' Acquisition Cost on the short-run margin, we calculate it, and show it in our supply curves of the efficiency resource, on a retail basis for easy and direct comparison with EIA prices and with readers' everyday experience,

Cost of saved energy. Following the standard Lawrence Berkeley National Laboratory convention, we express the cost of saving a unit of energy as a Cost of Saved Energy (CSE). CSE is the marginal cost of buying, installing, and maintaining the more efficient end-use device, divided by its discounted stream of lifetime energy savings. (Less technically, we spread the extra capital cost of an efficiency measure over its lifetime into equal annual payments at a sectorally appropriate discount rate, then divide that annual payment by the average annual savings.) Using the standard annuity formula, the dollar cost of saving, say, 1 bbl of petroleum fuel then equals $Ci/S[1-(1+i)^{-n}]$, where C is installed capital cost ($), i is annual real discount rate (shown above under "Money" for each sector), S is the rate at which the device saves energy (bbl/y), and n is its operating life (y). Thus at a societal discount rate (lower than we actually used in any sector's screening of eligible efficiency measures), a $100 device that saved 1 bbl/y for 10 y would have a CSE of $13/bbl. Against a $26/bbl oil price, a 20-y device with a 1-y simple payback would have a CSE of $2.1/bbl. Using the same formula, a $100 device that saved 1,000 kWh/y for 20 y at the 7%/y real discount rate we assumed for buildings would have a CSE of 0.9¢/kWh, and against a $0.15/kWh electricity price, a 20-y device with a 1-y simple payback would have a CSE of 1.4¢/kWh. CSEs can be negative if capital charges are more than offset by saved present-valued maintenance cost, avoided equipment, etc., making the net capital-and-maintenance cost less than zero. Our Cost of Saved Energy calculations do not include the transaction or program costs of implementation, though in low-designed programs these are generally very small.

Supply curves for energy efficiency. Engineering-oriented analysts conventionally draw efficiency "resources" as a supply curve (relating marginal savings to their marginal CSEs), rather than as a shift along a demand curve (economists' convention). This clarifies that CSE is methodologically equivalent to the cost of *supplied* energy, such as refined petroleum products or delivered electricity: *the value of the saved energy isn't part of the CSE calculation*, which shows only the cost of achieving the saving. Whether that saving is cost-effective depends on whether its CSE is more or less than the cost of the energy it saves, and on what costs are counted (private internal *vs*. full societal costs).

Combining energy savings. Successive energy savings don't add; they multiply. Each saving leaves less usage to be saved by the next. We count this effect fully: for example, three successive savings of 40% reduce energy use of 1.0 not by 0.4 + 0.4 + 0.4 = 1.2 (impossible!) but by $(1 - 0.6^3) = 0.78$, leaving 0.22. However, interactions between savings are far more complex and often very important in vehicles (Ch. 2); we count them largely or fully for light-duty road vehicles but probably less completely, understating the achievable savings, for trucks and ships.

Externalities. This analysis is framed in terms of private internal cost. It assumes that all negative or positive external costs (those not included in market prices, such as, at this writing, carbon emissions in the United States, or the cost of oil spills and smog-induced disease) are worth zero, although we don't actually believe that's the right number—just a conservative assumption. Positive externalities, such as increased labor productivity or health in well-designed efficient buildings, are likewise omitted, understating those buildings' benefits and real-estate value.

Subsidies. In the short term, we generally compare renewable with nonrenewable sources of electricity apples-to-apples, *i.e.*, each getting whatever U.S. subsidies it gets now. This accurately reflects the distorted prices for both as seen by their users. However, our long-term electricity analysis compares *un*subsidized renewable sources with nonrenewable sources that *continue* to get the permanent subsidies they now enjoy.

Rebound. People may drive more miles in more fuel-efficient cars because their fuel cost per mile drops. This implies that they value the increased mobility more than the cost of the fuel consumed. Such "rebound" can use more fuel, and this book is concerned with fuel use, not economic welfare. We discuss rebound explicitly for autos *(Reinventing Fire,* pp. 43 and 45 and note 92). For household space-conditioning, we assume rebounds of 10% for space heating, 5% for spacing cooling. We don't believe the technical literature on rebound (authoritatively reviewed by Sorrell 2007, 2009) convincingly demonstrates a material rebound effect for household appliances or in industry (*Reinventing Fire*, p. 145), nor has rebound been shown in commercial buildings—where in the leased majority of premises, the allocation of common costs, usually including space-conditioning, prorated on floorspace further vitiates any assumed service-price shift caused by energy savings. EIA's baseline forecast already includes a general 5% rebound, making EIA's assumed savings 5% smaller than they would otherwise have been. Our assumed aggregate rebound effects are smaller but we back out all EIA-forecast savings to avoid double-counting, those savings are generally modest, and our additional savings are calculated as a percentage of energy demand after EIA-forecast savings, so our different rebound assessment doesn't significantly affect our calculated potential savings.

Feedbacks. We explicitly model important feedbacks where we can anticipate them. For example, we model how automobiles sell faster when they're more economically attractive to buyers, and how rising auto sales accelerate cost reductions in their key technologies. We also model how, when autos are used more productively, decreasing vehicle-miles traveled, this somewhat slows vehicle sales, decelerating progress down those cost curves. Since the energy system interacting with many social and economic variables is almost infinitely complex, we probably have not captured all feedbacks, but we think our analysis reflects all the important ones. (Please see also the discussion above of why we didn't do a general-equilibrium calculation.).

Any methodologies, conventions, or descriptions that need further clarification should kindly be notified to rfsuggestions@rmi.org. Thank you.

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[i] A longer version, likewise from the Internet without stated citation, reads in more Eisenhower-like syntax: "Whenever I run into a problem I can't solve, I always make it bigger. I can never solve it by trying to make it smaller, but if I make it big enough, I can begin to see the outlines of a solution." Either way, the remark may be apocryphal: the scholars at the Eisenhower Library have kindly searched for it but have been unable to find it. Regardless, it has proven a powerful strategy for us and many others—it has been approvingly quoted by former House Speaker Newt Gingrich and former Defense Secretary Donald Rumsfeld—and it does seem to reflect Eisenhower's approach to tough problems, so whether or not he actually said it, he seems to be one of its intellectual parents. We first heard it from software pioneer Bill Joy in the form, "If you can't solve the problem, make it bigger."

[ii] J G Koomey, "Past performance is no guide to future returns: What can we really say about the future of economic, social, and technological systems?," UCB Forum on Nuclear Future, 10 Dec 2010, http://cstms.berkeley.edu/special-projects/nuclear-futures/program/.

[iii] *Nichomachean Ethics*, paraphrasing a combination of I:3.24 (Berlin 1094b) and I:7.26 (Berlin 1098a).