Extreme Efficiency: How Far Can We Go If We Really Need To?

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ABSTRACT

Many studies have looked at the cost effective potential for efficiency by examining the supply curves for saved energy in detail for major end uses. Yet virtually all of these studies rely on methodologies that are excessively conservative if the goal of policymakers is to meet aggressive climate change emissions reduction goals.

This paper looks at factors that expand the efficiency potential in the context of the need to meet an aggressive climate goal, and the desire to do so in a way that minimizes costs and enhances economic development. It discusses the potential for continuous improvement in efficiency technology and design approach and how this can produce innovations that have economic benefits beyond the value of energy savings.

It explores some of the reasons that the conservatisms used in previous studies are not in fact conservative in the context of meeting a goal such as atmospheric greenhouse gas concentration stabilization at 450 ppm or lower at least cost. It also looks at issues that have not been addressed comprehensively in previous studies, such as whole-system design and projecting the availability and cost effectiveness of advanced technologies in the context of climate policies that must correct massive failures of the market.

This paper also discusses how the limitations on efficiency imposed by the laws of physics should be considered, since they do not seem to impose any practical barriers to vastly-improved levels of efficiency in the context of a 20-50 year time frame.

Introduction

There is a large[1] but generally ignored[2] literature of studies on efficiency potential, virtually all of which pose answers to questions of how far we can go with energy efficiency. But how far a region or a nation can go with energy efficiency is not *one* well-defined question: it can be one of several different questions. Thus the answer will depend on a number of different conditions and constraints, which generally are not noted by authors or reviewers of these studies. These constraints are discussed in Section II.

By framing the question that potentials studies are answering more precisely, we can see that the answer to the question posed in this paper – how far can we go *if we really need to* – has virtually never been addressed. Instead, all of the potentials studies project levels of efficiency or levels of final energy demand that could be defended as being achievable reliably and

[1] A list of references to major potentials studies would be long, uninformative, and for all that incomplete; 11 of them are reviewed in Nadel, Shipley & Elliott 2004; another dozen are cited in Goldstein 2007. Also noteworthy since they address world potentials and not just U.S. are IEA 2006 and MGI 2007. An informal compilation of other potentials studies by John Scofield for the American Physical Society's 2008 study on energy efficiency found dozens of additional references. See also footnote 3.

[2] Both the Cheney National Energy Policy Development Group 2001 and the earlier National Energy Policy Development Group 1992 reports fail to discuss or reference any of these (or comparable) studies; other energy policy studies, such as EIA 2006, ignore them in the analyses of the economic effect of limitations on emissions that cause climate change.

realistically. Realism is assumed to mean under conditions in which high levels of energy use are a concern as opposed to a crisis, and in which efficiency has to be defended as an *alternative to conventional energy supply* rather than as the *understood first priority resource*.

In addition to these problems, virtually all[3] of the potential studies are subject to systematic biases that cause them to understate the real potential of efficiency if the challenge is to meet serious energy or emissions reductions goals. They are discussed in detail in Section III.

One of the crucial biases is the tendency for the studies not to report the *most likely* value of the efficiency potential for each energy efficiency measure, but rather to report a number that is unlikely to be overly optimistic. Thus, while most scientific analyses report on the value of a variable subject to uncertainty as a median (at the 50th percentile of the distribution of likely outcomes), virtually all efficiency studies only include measures if they have a trivially small likelihood of being overestimates of the efficiency available at a particular price.

Such an approach is claimed to be one of using "conservative" assumptions. Section IV discusses how assumptions that are conservative in certain contexts become not-at-all conservative in the context of meeting a greenhouse gas emissions target at least cost/greatest benefit. It suggests that for the purposes of managing climate change or global energy security, the types of assumptions usually characterized by the authors of potentials studies as "conservative" are in fact riskier assumptions, in terms of the economic consequences of being wrong, than reporting 50th percentile likely answers. This is discussed in Section IV.

How far can a nation or region go in efficiency if it is really motivated? It is not possible to answer this question rigorously despite the extensive literature on the subject, for reasons to be discussed in this paper. The first step in estimating an answer is to provide a methodology that addresses the limitations of current research. This in turn requires a rigorous identification of the issues, which is the goal of this paper.

What Does "the Technical Potential for Efficiency" Mean?

Potentials studies are attempts to answer very specific policy questions, but these questions are seldom stated explicitly in the reports.

The first studies of efficiency potential, which generally were framed as alternative scenarios for lowered energy usage, were initiated in the early 1970's. While the impetus for most such studies was the 1973 energy crisis, the California Legislature commissioned an earlier analysis (Ahern et al. 1975) in response to concerns that the coastline would be overwhelmed by the large number of power plants needed to meet future projected demands.

In this case, the specific policy question could be framed as "How many power plants can the state of California save by instituting defined efficiency policies, such as building codes and appliance standards?" This (not explicitly stated) question defined a conservative response as one that would not allow power plants to be cancelled due to efficiency actions unless the savings were 100% assured. Ahern et al.1975 got it right: its most aggressive scenario projected a reduction in annual electricity growth to 3%; actual growth was cut to 2.2%. Thus the report was conservative by its own definition and measured with full hindsight: if growth had been 4% the report could have been called overly optimistic.

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[3] A conspicuous exception to this general problem of bias is the work of the Rocky Mountain Institute, typified by Lovins 1990 and Lovins 1991.

This framing assumed a particular actor with defined authority and a set timeframe. The choice of actor and authority affects the answer in a significant way. For example, potentials studies performed for utilities limit their scope of measures to those that can be acquired by utility programs. They do not include efficiency that can only be acquired through regulation or measures that require national or international actions to commercialize new technologies.

Another important framing question is the motivation of the actor and the range of feasible policy options. A metaphor for both can be found in asking the question "how far is it possible for you to run tomorrow?" The answer depends: if the goal of the run is to get exercise, you will give a very different answer than if the goal of the answer is to save your life. In terms of feasible policy options and preparation, the answer will be vastly different if, on one hand, you have a personal disinterest in running, or on the other hand, an executed physical training plan that had you working out for the past 2 years.

Virtually all efficiency potentials studies were developed in a context that limited the scope of acquisition actions to well below that which society has at its disposal if confronting a climate crisis, or by advocates of environmental protection who recognized that their enthusiasm might not be shared by policy decisionmakers and thus that overly aggressive assumptions would undercut their credibility.

But motivation is important in establishing actual potentials. When refrigerator manufacturers were confronted in 1984 with a mandatory standard for 1992 that could not be met by a single product currently in the market, they made much faster gains in efficiency than anyone (including themselves) had predicted. When this motivation was compounded by financial incentives to go beyond the standard, manufacturers turned out to be able to beat the standard by 10% and 15% the very year it went into effect, and by up to 40% three years later (Goldstein 1994). In the home retrofit area, after years of modestly-funded utility-run incentive programs produced market shares at best in the neighborhood of 20%, a program in Hood River, Oregon that attempted to retrofit a whole town in 3 years succeeded with various indicators of market penetration measured at around 90%. In this case, the motivation was, from the program implementer's side, a commitment to show what really could be done and from the homeowner's side, the motivation was that the utility paid the entire cost of the upgrade.

Both motivation and preparation were factors in California's dramatic success in curbing peak electric power in 2001. By the end of the year 2000, California faced a predicted 40 days of rolling blackouts the next summer and excess cost of electricity of $40 billion or more than $1,000 per capita (Goldstein 2007). This was sufficient motivation to quadruple the size of the state's energy efficiency incentive program ("preparation") and to provide advertisements, public information, and social reinforcement for lifestyle-based conservation that worked.

Systematic Biases Resulting in Low Potentials in Energy Efficiency Studies

Potential studies range from relatively simple analyses to extremely data-rich and complex ones. The clients and the researchers vary dramatically. But despite this immense diversity, virtually all of these studies have in common a series of self-proclaimedly "conservative" assumptions that may be appropriate for the context in which the studies were performed but are inappropriate for the purpose of national policymaking on energy efficiency (see Section IV below). This section discusses several of the most important of these biases:

Subjecting Efficiency Measures to a Criterion of Proof Beyond a Serious Doubt

When the first potentials studies were published, efficiency was a new concept. The very idea that energy efficiency was possible – stated precisely, that energy services could be provided with equal (or better) quality with less use of energy economy-wide--faced a skeptical audience. Conventional wisdom at that point was that energy use grew inexorably with economic output; stated colloquially, people believed that “energy is the lifeblood of the economy” and that constraining energy growth in any way constrained economic growth. Even today, these old nuggets of conventional wisdom still have political salience to significant numbers of people.

In this social/political context, studies of efficiency potential, to be successful, had to address themselves to a highly skeptical audience. Errors of excessive optimism in a study would undercut the credibility not only of a particular calculation but of the researcher and even the institution performing the work. Such consideration would cause the authors to define “conservative” assumptions as those that understated the likely magnitude of each measure in the efficiency resource. This problem is still with us.[4]

Thus, almost all potentials studies address uncertainty by intentionally biasing the assumptions (lowering energy savings projections and/or raising cost projections) to the point that there is little technical doubt that the predicted cost of saved energy for each measure in the supply curve will not be lower than what is subsequently found in the real world.[5]

This definition of conservative is not maladaptive. The one research organization that consistently refuses to follow it—Rocky Mountain Institute—is not often cited in policy discussions of how far one can go with efficiency. It seems that their credibility is adversely affected by the perception that their work contains errors of excess optimism.

This dynamic is particularly important in the industrial sector, where the same engineers doing the potentials study may become responsible for achieving the results in it. A study that projects a 25% savings potential with a 3 year payback will make its authors look bad if they achieve only a 21% savings at a 4 year payback, even though the achieved results are quite good.[6]

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[4] One must consider the political environment in which two of the most visible studies—Inter-Lab 1999 and Inter-Lab 2000—were conducted to see some of the motivation for this definition of conservatism. Both the former “Five-Lab” study and latter *Clean Energy Future* were prepared by DOE-funded laboratories in the context of considerable skepticism politically over the reality of the climate problem and the feasibility of mitigating it at a moderate cost. It was clear that any example, no matter how small, of excessive optimism, unjustified by the way the weight of evidence, concerning the cost-effectiveness or feasibility of an efficiency measure would come back to haunt not only the individual researcher who made the mistake but the director of the study at the highest levels, and the lab directors and political appointees at DOE. On the other side, an error of pessimism would hardly be noted and would cause no career damage or institutional funding risk.

[5] For example, one of the more aggressive studies, Meyer 1991, states that it “did not include… measures for which there was substantial uncertainty regarding their costs, savings potential, or date of availability.” IEA 2006 states that “This [study] conservatively assumes no major advanced in lighting technology.”

[6] In some business environments, a CEO who sees a study showing precisely how to save 25% could decide that the corporate goal should be to double that and save 50%. A potentials study that gave an unbiased result as to the savings most likely to be achievable would get its authors in trouble.

Assuming Arbitrary Realization Factors Less than 100% Due to Questions about Social Acceptance of Energy Efficiency

Energy efficiency decisions are made by millions of individual businesses or households in the context of the constraints of the marketplace, so after analyzing the technical feasibility of a measure, potential studies generally evaluate the "achievable potential," accounting for constraints that might prevent the studies' client from obtaining full adoption. The reduction factors are by nature judgmental. Thus they will be more limiting in response to the question posed in the individual study than appropriate in response to the question posed here.

For example, Inter-Lab 1997 sets a limit of 65% on the market share of technologies in its most advanced scenario that assumes $50/ton carbon charges. But market shares greatly exceeding 65% have been observed wherever the motivation to acquire the resource is strong: both with mandatory programs and in incentive programs where the measures were offered for free.[7]

Inter-Lab 2000, by contrast, picks non-controversial (biased towards high likelihood of success) levels of standards for the measures where it assumes 100% market penetration. Its advanced energy efficiency scenario shows a maximum air conditioner standard of SEER 12. In fact, the current standard that went into effect in 2006 is SEER 13, and where there are state incentive programs they yielded a 15% market share of SEER 15+ products for calendar year 2006 (of which 6% are at SEER 16). Clearly higher market shares are feasible it the will and/or the budgets are there.

An Implicit Assumption that a Lack of Research on the Cost or Feasibility of a Particular Measure Means that It Is Excluded from the Study

Most supply curves consist of relatively large resources at cost of conserved energy of one-third to one-half of the cost of conventional supply (or less).[8] This is evidence of an environment in which there is little or no market incentive to introduce a measure with a cost of saved energy about equal to the alternatives: if 2 or 3-year paybacks are going begging, there won't be much market data on 6 and 12-year paybacks because no one is introducing the technologies. This means a dearth of easily-accessible research data: instead of seeking products that are commercially available, the researcher has to imagine products that *might* be commercially available and come up with a cost for them. This is generally too difficult to do in the context of a potential study; therefore these points are left out.

There is a similar problem with respect to the smaller uses of energy. If there is not much information available on, for example, the efficiency potential of home copiers, most studies assume that there is no potential. And since "miscellaneous" is a large category for both residential and commercial buildings, this is not a trivial problem.

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[7] Both the Hood River Conservation Project and the Pacific Gas & Electric Delta Project achieved retrofit market penetrations for an advanced package of measures of about 90% by having the utility pay 100% of the costs. While this is not a likely policy in 2008, it is certainly feasible and from an economics perspective it could well be more cost-effective than doing nothing. Retrofitting all the homes in the U.S. with all cost effective measures this way would cost the government about $500 billion. The yearly cost is about half of the amount the Congress spent on "economic stimulus" in 2008 trying to solve a problem much less cosmic than climate change in a manner less effective at stimulating the economy than home retrofits.

[8] California's retrospective evaluation of utility programs shows a benefit/cost ratio of about 2 or 3:1, corroborating these estimates based on field experience.

In some cases, the research needed to answer the question is essentially to try to implement the policy. It is impossible to determine from open literature a good answer to the question of whether a more efficient widget could be produced by the millions at reasonable cost: the needed information is competitively sensitive at best and not even known by the manufacturers at worst. The best way to do the potentials study may be to implement the incentive needed to create the production, at least on a pilot scale.

A Failure to Consider Issues of Systems Integration

It is a lot easier to conduct a potentials study with the structure of a spreadsheet with each individual component having its own piece of the supply curve[9] than it is to construct a whole-buildings efficiency supply curve. Yet, by imposing a constraint on the economic optimization of the system – namely that only measures that apply to individual components be considered – the analysis necessarily limits both the extended efficiency projected to be feasible and the cost-effectiveness of measures at the frontiers.

This is an important issue in buildings, where a recent analysis of how much energy could be saved in commercial buildings as a result of prescriptive, component-based measures showed savings at 20%-35% compared to ASHRAE 90.1-2004 and IECC 2006 were feasible. (NBI 2007) But practitioners of energy efficiency design or research who have experience with state-of-the-art buildings agree that 50% savings, based on an integrated whole buildings approach, not only are technically feasible but are generally more cost-effective than the lower percentage savings based on component redesign.[10]

Considering systems integration is more difficult of a research task, and that is one likely reason that it is not done. It also provides less credibility to the skeptic: a study that says one can achieve a 60% (for example) reduction in office building HVAC energy use and cites dozens of examples will be less convincing to skeptics than a laundry list of individual measures, each of which can be costed separately and each of which has technical performance characteristics that are easy to describe.

An Assumption that Once Known Efficiency Measures Are Implemented, Technological Progress Ceases and No Further Improvements Are Possible

With only one or two exceptions, potential studies limit themselves to technologies that are either commercially available or readily visible on the horizon. But that is not how real technology advancement works in markets that are functional. In practice, once efficiencies have improved for a particular end-use device, the potential for further reductions does not disappear: virtually no matter how large the initial improvement was, more new potential is developed. As soon as a stringent new standard takes effect, designers and manufacturers have always found additional ways that efficiency can be improved. Thus for end uses where the greatest progress

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[9] The researcher would have to account for interactions between measures, but all the studies the author has reviewed have done this.

[10] Personal communications, Mark Hansen, Jason F. McLennan, Mark Frankel, Marcus Sheffer, Tom Marseille. The fact that this reference is not based on peer reviewed publications illustrates the very problem of bias that this paper discusses: many authors would delete the finding for "conservatism" and deprive the reader of real, if not authoritative, data on advanced levels of efficiency. Such an action would lead the reader to assume that 30% was the maximum efficiency potential, rather than being able to evaluate the data and its provenance as the reader of this paper can do.

has been made, such as refrigerators or home heating, there is clear evidence supporting the ability to do 20% to 50% better cost effectively, where for products where little progress has been made, such as water heaters or clothes dryers, there is little potential that can be demonstrated without controversy.

The issue of failures of the market is important in understanding and evaluating the extent of future efficiency improvements that are possible. Efficiency potentials that are cost-effective only exist because of market failures: if the markets were functioning, all of the cost-effective potential continuously would be realized. But because market failures are so pervasive and deep, for most end uses, two-year paybacks are lying around unexploited. When this is the case, it does not make sense for manufacturer and designers to put much effort into offering even higher efficiency options that might have 3 or 5 year paybacks. So a vicious circle is created in which technological progress is thwarted because even the current generation of products does not sell very well. Overcoming market failures conversely can create affirmative incentives for continual improvement in energy efficiency.

This dynamic also means that researchers doing potentials studies lack data on what markets could do and thus tend to rely on data derived from real markets, which are limited to 3 year paybacks. When the potentials study is intended for guiding resource acquisition, for example by a utility or state energy office, this lack of data on more advanced levels of efficiency creates another vicious circle: when the potentials studies fail to account for these future improvements, no one tries to acquire them.

Where these market failures are absent—for markets in which competitive forces reward innovation and improved performance—we see continuous improvement. In the computer chip industry, "Moore's Law" predicts exponential growth in computing power with a doubling time of 18 months. While it seemed intuitive that this relationship would have to break down at some point, it has been surprisingly long lived. Similarly in the data storage field, in the mid 1990s a portable storage device stored less than 1½ Megabyte (and even that was a major improvement compared to the 200-400 kilobyte "floppy disks" of the 1980s); today cheap DVD media can store 5-8 GB. The best portable computer hard drives had about 100 Megabyte capacity, (Farrance 2006) while in 2008 it is not expensive to buy 4 Terabyte drives. The first digital camera in 1995 had 1.3 megapixels and cost about $17,000; in 2008 the comparable product has 21 megapixels and costs less than half as much, an annual rate of improvement in quality of about 25%;[11] while pocket sized cameras have 12 megapixels and cost less than $400. The latter example is also an apparently exponential improvement cycle but with a much slower rate.

The point of this comparison is to suggest that if market-based policies made it profitable to make continuous improvements in efficiency, we would see similar trends (if not rates) of improvement. And conversely, if we asked whether there were any potentials studies indicating in advance that these industries were capable of orders-of-magnitude improvements in 20 years, it is doubtful that any such study was done. Instead, the industries responded incrementally to market opportunity.

[11] The first camera was a Canon DCS 3 introduced in July 1995 for ¥ 2 million (about $17,000); six months later a 6 megapixel version was made but cost ¥ 3.6 million; using the latter as a base would yield an improvement rate of 10% per year. Source: Canon.com "Camera Museum," posted in 2007.

The challenge for climate planning would be to estimate what annual rate of improvement is most reasonable to expect from each end use based on future technology development.[12] These factors would be used to estimate future potentials after the potentials of existing technologies as already documented are exhausted.

Ignoring the Economic Value of Non-Energy Benefits Such As Increased Thermal Comfort at Higher Levels of Information, or Increased Productivity of High Efficiency Commercial Space

For several major end uses, and probably for most of them, energy efficiency measures also deliver non-energy benefits.[13] These benefits may exceed, or even greatly exceed, the economic value of the energy savings themselves. Yet they are almost never included in efficiency potentials studies in a way that affects how measures are ranked in terms of cost of saved energy[14]. An energy efficiency measure that is cost-effective at 10¢/kWh is calculated to be cost-effective because the incremental cost of the measure divided by the discounted value of energy savings alone gives 10¢. This is equivalent to cutting off the threshold for cost-effectiveness at an arbitrarily low cost of saved energy.

In other cases, non-energy benefits accrue when manufacturers have to redesign a production process to improve the energy efficiency of the product and realize that as long as they are redesigning the manufacturing process for a better product, they can also optimize for production efficiency. This benefit can be seen from the cases where the costs of the more efficient product are no higher than that of its predecessor. This case is best illustrated by the cost trajectory for American refrigerators (Goldstein 2007).

In some cases, the problem can be rationalized by the uncertainty in quantifying the value of non-energy benefits. But, taking a parameter with a large and positive but uncertain value and assigning it a known value of zero is not a scientifically valid approach.

A Reliance on <u>Projected</u> Costs of Efficiency Without Looking at <u>Realized</u> Costs, Which, Whenever Data Has Been Available, Have Always Been Lower than Projected Costs and Often Lower than Zero

Potentials curves are based on incremental costs that are projected from looking at products or design services at an immature market stage when they represent typically a fifth of the market or even less. (If this weren't the case, potentials would revolve around taking 80% market shares and increasing them to 100%, which is almost never the case.)

But, policies that induce large changes in market share also induce reductions in price through several different economic mechanisms. This effect has been observed in practice and is also the expected result from economic theory (Goldstein 2007).

[12] For examples of end uses where policy promoted energy efficiency with some level of consistency, the rate of improvement for refrigerator energy efficiency for the period 1972-2005 is about 4-5% annually, with the lower number representing the rate of decrease of the sales weighted average while the higher refers to the rate for the most popular class—top freezer models—and ignores changes in class mix. The rate of improvement of air conditioning efficiency in California houses from 1970 to 2006 was 3-4.5%, with the lower figure referring to whole-house cooling energy and the latter to cooling energy per unit floor area.

[13] A few measures may also have non-energy costs (CFLs have both), but the costs are small, by definition: if they were large, the measure would be excluded from the potential for this reason.

[14] Again, the Rocky Mountain Institute is an exception. But they have been criticized for taking this approach.

Ignoring the Economic Benefits of Reductions in Energy Price Due to Reductions in Demand with the Same Amount of Supply

American and global economic experience over the last several years has shown that the price of major market-traded energy commodities such as natural gas and crude oil is highly dependent on a narrow balance between supply and demand. Very small changes in demand leverage very large changes in price: short-term elasticities are far in excess of 1.

The effect of reducing energy prices can be large. For the case of gas furnaces, one analysis show that the benefits of a hypothetical energy efficiency standard in terms of reducing gas prices to non-users of the regulated product vastly exceeded the benefit in terms of lower quantities consumed to the users themselves. (Goldstein 2004) No potentials study has quantified this effect.

What Is a Conservative Assumption?

Virtually all efficiency potentials studies were designed by their authors to be "conservative." But depending on the intended use of the study, "conservative" has different meanings. For example, if you are considering whether you can afford a new car for your business use, a conservative calculation of your budget means that you assume your income is at the lowest level you can expect. If you can make the payments at this level, then you can afford the car. A conservative calculation means that your risk of being *optimistically wrong* is near zero. But is also means that you will in all of the most likely cases be able to afford a lot more.

If the purpose of the calculation is to determine whether it is prudent for you to borrow money to buy the car, this definition of conservative is appropriate.

But if the purpose is to calculate your estimated taxes, it is not: the assumption that your income is low mean that you will underestimate your taxable profit, and so you will underestimate your tax liability and be subject to IRS penalties.

For some purposes, such as cancelling a planned power plant based on efficiency potentials, a conservative approach is to bias against efficiency: if you are overly optimistic in this case, the risk of power shortages increases. If there is a distribution of likely answers to the question of the size of the efficiency potential, one should pick the number at the low end of the range.

But for the purpose of planning for minimizing climate change, this is the wrong approach. The right answer of the size of the efficiency wedge is at the *median (50th percentile) level* of the probability distribution of the potential. This is the right policy approach because the consequences of assuming the efficiency potential is less than it really could be is that less policy attention is paid to efficiency, which means that more attention and money are devoted to other solutions that are more expensive than efficiency in terms of cost per ton of emissions abatement. Since these strategies are at least two times more expensive than efficiency, as observed in evaluations, underestimating the efficiency resource by $1 will raise the overall cost of compliance by $1 (by using the $2 alternate rather than $1 efficiency).

The prospective error in <u>underestimating</u> the efficiency potential in the context of a binding carbon cap is much larger than the consequences of <u>overestimation</u>. The consequence of overestimation is that alternative emissions reduction investments will be needed with less lead time. They would have been needed anyway even if the potential for efficiency had been estimated correctly. So the only economic loss is that the low carbon resources that would need to be built anyway will be built more quickly than if the efficiency resource had been predicted accurately. The extra cost due to delay in starting to build these alternatives should not be a 100% effect but more of a 10% effect.

How much Energy Do We Really Need?

The answer to this question requires examination the major uses of energy to see if we can achieve high levels of energy service for radically lower, or even zero consumption of energy. This had not really been done on a comprehensive basis, although the concept was introduced long ago (APS 1975); and until it is, the question that this paper poses will not be fully answerable analytically.

Perhaps the closest we have come is a set of studies on building efficiency summarized in Brohard 1997. This study looks at metered results of buildings designed to demonstrate maximum energy efficiency that could be obtainable economically on a widespread basis in one region. It found savings of 50%-70% for new construction and 40%-50% for retrofits, a higher savings fraction than in any potentials study (other than Rocky Mountain Institute research, which suggests 75% savings).

A more detailed approach would look at all the major end uses of energy and identify what the practical limits were to cost effective efficiency, using existing and foreseeable technology. Unfortunately, this research has not been done recently.

But even a cursory examination of the physics of the major uses of energy: heating of space and water, lighting, cooling, ventilation, and personal transportation, shows that when there are limits to plausible efficiency levels, they are an order of magnitude or more higher than current efficiencies. For example, there is no physical limit to how much insulation a building can use to cut heating use, and at some point the heat generated by sunlight entering the windows is sufficient to supply this need. Similarly, cooling can be reduced dramatically by eliminating sources of heat gain such as solar heat through windows and conducted heat through walls and by efficiencies in other end uses that end up as cooling loads, while ventilation heat gains can be reduced by latent and sensible heat recovery. Better urban design can reduce the need to drive cars by over two thirds, while the car itself could use at least an order of magnitude less energy.

Conclusions

The careful reader will note that this paper has not yet posited an answer to the question posed in the title. This omission is a consequence of the observation that there is a fundamental tradeoff between rigor and accuracy in trying to estimate a quantitative answer. The research to support a quantitative estimate of how far energy use can be lowered *if we really needed to* does not yet exist, nor is there a well-articulated methodology to guide such research. This paper has describes why the abundant literature on the subject answers questions different from the one framed in the title. It also discusses why even if the question had been framed as suggested herein, systematic biases would cause studies to understate the potential that could really be acquired through aggressive but still cost-effective policy means. By identifying both the need to frame the question properly and by listing some of the biases that need to be removed, this paper is intended as a first step toward developing such a methodology.

One of the key variables in attempting to answer the question of how much energy efficiency we could achieve if we really tried is the exponent in Moore's law: if markets rewarded incremental improvements in efficiency, what annual rate of improvement could we project? This is coupled to the question of where the physical limits are, if they exist, that would stop exponential improvement in efficiency after some point.

Absent detailed analysis, the author estimates that savings of 80%-90% are possible for major end uses within 1-2 decades, plus some lag time for stock turnover. This estimate is corroborated by the 2030 Challenge, which calls for all new buildings to be net zero energy users by 2030, and is endorsed by ASHRAE, the American Institute of Architects, the U.S. Conference of Mayors, the U.S. Green Building Council and others.

The difference between the rigorous (but biased) answer to the wrong question obtained from the literature — somewhere between 35% and 50% savings after 20-40 years — and the hypothesized right answer to the posed question — 80% to 90% or more — is less important than it might appear. Even 35% savings is an ambitious goal that will require a major increase in policy activity and budgets. Savings that could be acquired by introducing next-generation technologies that will only be realized if we are successful with the current generation.

The path to 80+% savings goes through realizing 35%-50%. Continuation and refinement of the policies that got us the first 35% will allow us to discover and acquire the remaining potential.

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