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solutions

Forget Nuclear

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Nuclear power, we're told, is a vibrant industry that's dramatically reviving because it's proven, necessary, competitive, reliable, safe, secure, widely used, increasingly popular, and carbon-free—a perfect replacement for carbon-spewing coal power. New nuclear plants thus sound vital for climate protection, energy security, and powering a growing economy.

There's a catch, though: the private capital market isn't investing in new nuclear plants, and without financing, capitalist utilities aren't buying. The few purchases, nearly all in Asia, are all made by central planners with a draw on the public purse. In the United States, even government subsidies approaching or exceeding new nuclear power's total cost have failed to entice Wall Street.

This non-technical summary article compares the cost, climate protection potential, reliability, financial risk, market success, deployment speed, and energy contribution of new nuclear power with those of its low- or no-carbon competitors. It explains why soaring taxpayer subsidies aren't attracting investors. Capitalists instead favor climate-protecting competitors with less cost, construction time, and financial risk. The nuclear industry claims it has no serious rivals, let alone those competitors—which, however, already outproduce nuclear power worldwide and are growing enormously faster.

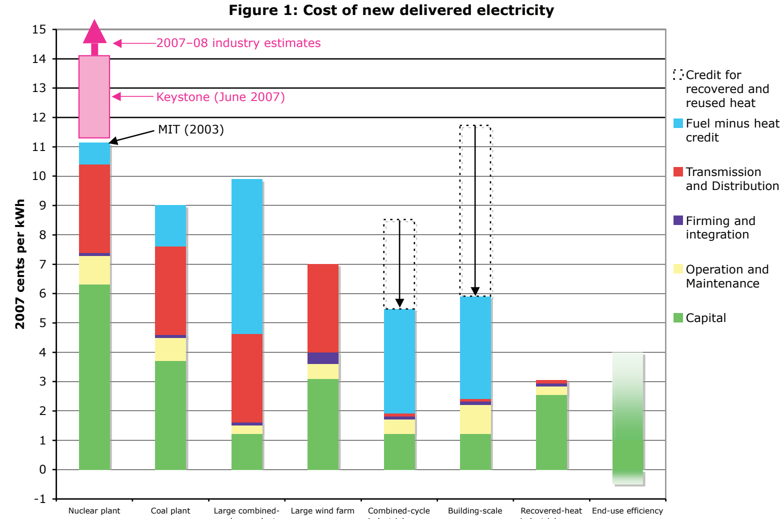
Most remarkably, comparing all options' ability to protect the earth's climate and enhance energy security reveals why nuclear power could never deliver these promised benefits even if it could find free-market buyers—while its carbon-free rivals, which won $71 billion of private investment in 2007 alone, do offer highly effective climate and security solutions, sooner, with greater confidence.

Uncompetitive Costs

The Economist observed in 2001 that "Nuclear power, once claimed to be too cheap to meter, is now too costly to matter"—cheap to run but very expensive to build. Since then, it's become several-fold costlier to build, and in a few years, as old fuel contracts expire, it is expected to become several-fold costlier to run. Its total cost now markedly exceeds that of other common power plants (coal, gas, big wind farms), let alone the even cheaper competitors described below.

Construction costs worldwide have risen far faster for nuclear than non-nuclear plants, due not just to sharply higher steel, copper, nickel, and cement prices but also to an atrophied global infrastructure for making, building, managing, and operating reactors. The industry's flagship Finnish project, led by France's top builder, after 28 months' construction had gone at least 24 months behind schedule and $2 billion over budget.

Figure 1: Cost of new delivered electricity



By 2007, as Figure 1 shows, nuclear was the costliest option among all main competitors, whether using MIT's authoritative but now low 2003 cost assessment,[1] the Keystone Center's mid-2007 update (see Figure 1, pink bar), or later and even higher industry estimates (see Figure 1, pink arrow).[2]

Cogeneration and efficiency are "distributed resources," located near where energy is used.

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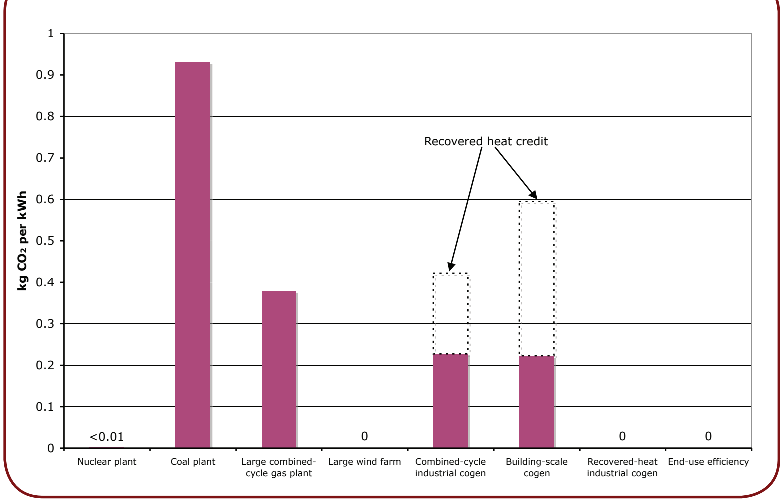

Figure 2: Operating CO_2 emitted per delivered kWh

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Therefore, they don't incur the capital costs and energy losses of the electric grid, which links large power plants and remote wind farms to customers.[3] Wind farms, like solar cells,[4] also require "firming" to steady their variable output, and all types of generators require some backup for when they inevitably break. The graph reflects these costs.

Making electricity from fuel creates large amounts of byproduct heat that's normally wasted. Combined-cycle industrial cogeneration and building-scale cogeneration recover most of that heat and use it to displace the need for separate boilers to heat the industrial process or the building, thus creating the economic "credit" shown in Figure 1. Cogenerating electricity and some useful heat from currently discarded industrial heat is even cheaper because no additional fuel is needed.[5]

End-use efficiency lets customers wring more service from each kilowatt-hour by using smarter technologies. As RMI's work with many leading firms has demonstrated, efficiency provides the same or better services with less carbon, less operating cost, and often less up-front investment. The investment required to save a kilowatt-hour averages about two cents nationwide, but has been less than one cent in hundreds of utility programs (mainly for businesses), and can even be less than zero in new buildings and factories—and in some retrofits that are coordinated with routine renovations.

Wind, cogeneration, and end-use efficiency already provide electrical services more cheaply than central thermal power plants, whether nuclear- or fossil-fuelled. This cost gap will only widen, since central thermal power plants are largely mature while their competitors continue to improve rapidly. The high costs of conventional fossil-fuelled plants would go even higher if their large carbon emissions had to be captured.

Uncompetitive CO_2 Displacement

Nuclear plant operations emit almost no carbon—just a little to produce the fuel under current conditions.[6] Nuclear power is therefore touted as the key replacement for coal-fired power plants. But this seemingly straightforward substitution could instead be done using non-nuclear technologies that are cheaper and faster, so they yield more climate solution per dollar and per year. As Figure 2 shows, various options emit widely differing quantities of CO_2 per delivered kilowatt-hour.

Coal is by far the most carbon-intensive source of electricity, so displacing it is the yardstick of carbon displacement's effectiveness. A kilowatt-hour of nuclear power does displace nearly all the 0.9-plus kilograms of CO_2 emitted by producing a kilowatt-hour from coal. But so does a kilowatt-hour from wind, a kilowatt-hour from recovered-heat industrial cogeneration, or a kilowatt-hour saved by end-use efficiency. And all of these three carbon-free resources cost at least one-third less than nuclear power per kilowatt-hour, so they save more carbon per dollar.

Combined-cycle industrial cogeneration and building-scale cogeneration typically burn natural gas, which does emit carbon (though half as much as coal), so they displace somewhat less net carbon than nuclear power could: around 0.7 kilograms of CO_2 per kilowatt-hour.[7] Even though cogeneration displaces less carbon than nuclear does per kilowatt-hour, it displaces more carbon than nuclear does per dollar spent on delivered electricity, because it costs far less. With a net delivered cost per kilowatt-hour approximately half of nuclear's, cogeneration delivers twice as many kilowatt-hours per dollar, and therefore displaces around 1.4 kilograms of CO_2 for the same cost as displacing 0.9 kilograms of CO_2 with nuclear power.

Figure 3 compares different electricity options' cost-effectiveness in reducing CO_2 emissions. It counts both their cost-effectiveness, in delivering kilowatt-hours per dollar, and their carbon emissions, if any.

Nuclear power, being the costliest option, delivers less electrical service per dollar than its rivals, so, not surprisingly, it's also a climate-protection loser, surpassing in carbon emissions displaced per dollar only centralized, non-cogenerating combined-cycle power plants burning natural gas.[8] Firmed windpower and cogeneration are 1.5 times more cost-effective than nuclear at displacing CO_2. So is efficiency at even an almost unheard-of seven cents per kilowatt-hour. Efficiency at normally observed costs beats nuclear by a wide margin—for example, by about ten-fold for efficiency costing one cent per kilowatt-hour.

New nuclear power is so costly that shifting a dollar of spending from nuclear to efficiency protects the climate several-fold more than shifting a dollar of spending from coal to nuclear. Indeed, under plausible assumptions, spending a dollar on new nuclear power *instead* of on efficient use of electricity has a worse climate effect than spending that dollar on new coal power!

If we're serious about addressing climate change, we must invest resources wisely to expand and accelerate climate protection. Because nuclear power is costly and slow to build, buying more of it rather than of its cheaper, swifter

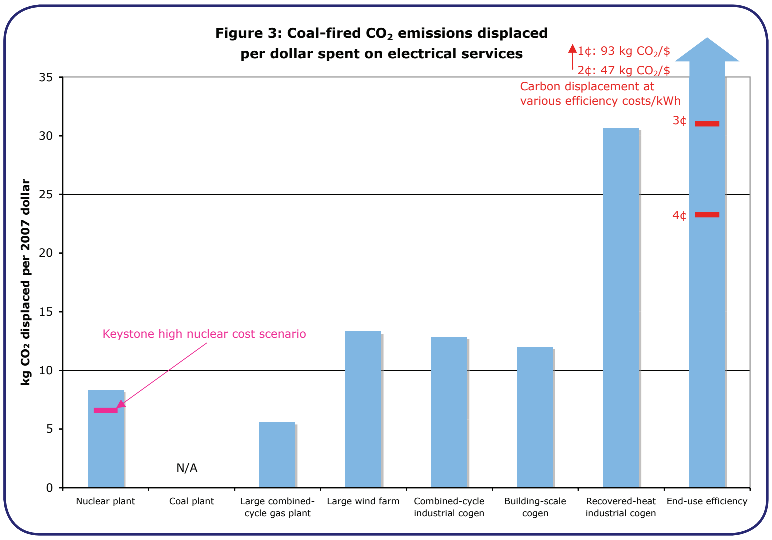


Figure 3: Coal-fired CO_2 emissions displaced per dollar spent on electrical services

rivals will instead reduce and retard climate protection.

Questionable Reliability

All sources of electricity sometimes fail, differing only in why, how often, how much, for how long, and how predictably. Even the most reliable giant power plants are intermittent: they fail unexpectedly in billion-watt chunks, often for long periods. Of all 132 U.S. nuclear plants built (52 percent of the 253 originally ordered), 21 percent were permanently and prematurely closed due to reliability or cost problems, while another 27 percent have completely failed for a year or more at least once. Even reliably operating nuclear plants must shut down, on average, for 39 days every 17 months for refueling and maintenance. To cope with such intermittence in the operation of both nuclear and centralized fossil-fuelled power plants, which typically fail about 8 percent of the time, utilities must install a roughly 15 percent "reserve margin" of extra capacity, some of which must be continuously fuelled, spinning ready for instant use. Heavily nuclear-dependent regions are particularly at risk because drought, a serious safety problem, or a terrorist incident could close many plants simultaneously.

Nuclear plants have an additional disadvantage: for safety, they must instantly shut down in a power failure, but for nuclear-physics reasons, they can't then be quickly restarted. During the August 2003 Northeast blackout, nine perfectly operating U.S. nuclear units had to shut down. Twelve days of painfully slow restart later, their average capacity loss had exceeded 50 percent. For the first three days, just when they were most needed, their output was below 3 percent of normal.

The big transmission lines that highly concentrated nuclear plants require are also vulnerable to lightning, ice storms, rifle bullets, and other interruptions. The bigger our power plants and power lines get, the more frequent and widespread regional blackouts will become. Because 98–99 percent of power failures start in the grid, it's more reliable to bypass the grid by shifting to efficiently used, diverse, dispersed resources sited at or near the customer. Also, a portfolio of many smaller units is unlikely to fail all at once: its diversity makes it especially reliable even if its individual units are not.

The sun doesn't always shine on a given solar panel, nor does the wind always spin a given turbine. Yet if properly firmed, both windpower, whose global potential is 35 times world electricity use, and solar energy, as much of which falls on the earth's surface every ~70 minutes as humankind uses each year, can deliver reliable power without significant cost for backup or storage. These variable renewable resources become *collectively* reliable when diversified in type and location and when integrated with three types of resources: steady renewables (geothermal, small hydro, biomass, etc.), existing fuelled plants, and customer demand response. Such integration uses weather forecasting to predict the output of variable renewable resources, just as utilities now forecast demand patterns and hydropower output. In general, keeping power supplies reliable despite large wind and solar fractions will require less backup or storage capacity than utilities have already bought to manage big thermal stations' intermittence. The myth of renewable energy's unreliability has been debunked both by theory and by practical experience.

Large Subsidies to Offset High Financial Risk

The latest U.S. nuclear plant proposed is estimated to cost $12–24 billion (for 2.2–3.0 billion watts), many times industry's claims, and off the chart in Figure 1 above. The utility's owner, a large holding company active in 27 states, has annual revenues of only $15 billion. Such high, and highly uncertain, costs now make financing prohibitively expensive for free-market nuclear plants in the half of the U.S. that has restructured its electricity system, and prone to politically challenging rate shock in the rest: a new nuclear kilowatt-hour costing, say, 16 cents "levelized" over decades implies that the utility must collect ~27 cents to fund its first year of operation.

Lacking investors, nuclear promoters have turned back to taxpayers, who already bear most nuclear accident risks and have no meaningful say in licensing. In the United States, taxpayers also insure operators against legal or regulatory delays and have long subsidized existing nuclear plants by ~1–5¢ per kilowatt-hour. In 2005, desperate for orders, the politically potent nuclear industry got those subsidies raised to ~5–9¢ per kilowatt-hour for new plants, or ~60–90 percent of their entire projected power cost. Wall Street still demurred. In 2007, the industry won relaxed government rules that made its 100 percent loan guarantees (for 80 percent-debt financing) even more valuable—worth, one utility's data revealed, about $13 billion for a single new plant. But rising costs had meanwhile made the $4 billion of new 2005 loan guarantees scarcely sufficient for a single reactor, so Congress raised taxpayers' guarantees to $18.5 billion. Congress will be asked for another $30+ billion in loan guarantees in 2008. Meanwhile, the nonpartisan Congressional Budget Office has concluded that defaults are likely.

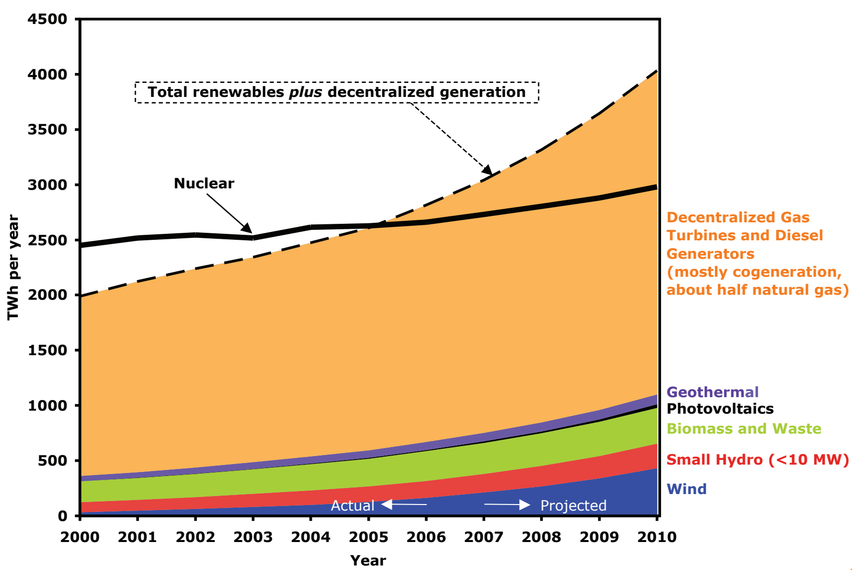
Wall Street is ever more skeptical that nuclear power is as robustly competitive as claimed. Starting with Warren Buffet, who just abandoned a nuclear project because "it does not make economic sense," the smart money is heading for the exits. The Nuclear Energy Institute is therefore trying to damp down the rosy expectations it created. It now says U.S. nuclear orders will come not in a tidal wave but in two little ripples—a mere 5–8 units coming online in 2015–16, then more if those are on time and within budget. Even that sounds dubious, as many senior energy-industry figures privately agree. In today's capital market, governments can have only about as many nuclear plants as they can force taxpayers to buy.

The Micropower Revolution

While nuclear power struggles in vain to attract private capital, investors have switched to cheaper, faster, less risky alternatives that *The Economist* calls "micropower"—distributed turbines and generators in factories or buildings (usually cogenerating useful heat), and all renewable sources of electricity except big hydro dams (those over ten megawatts). These alternatives surpassed nuclear's global capacity in 2002 and its electric output in 2006. Nuclear power now accounts for about 2 percent of worldwide electric capacity additions, vs. 28 percent for micropower (2004–07 average) and probably more in 2007–08.

An even cheaper competitor is end-use efficiency ("negawatts")—saving electricity by using it more efficiently or at smarter times. Despite subsidies generally smaller than nuclear's, and many barriers to fair market entry and competition, negawatts and micropower have lately turned in a stunning global market performance. Micropower's actual and industry-projected electricity production is running away from nuclear's, not even counting the roughly comparable additional growth in negawatts, nor any fossil-fuelled generators under a megawatt (see Figure 4).[9]

Figure 4: Low- or no-carbon worldwide electrical output (except large hydro)



The nuclear industry nonetheless claims its only serious competitors are big coal and gas plants. But the marketplace has already abandoned that outmoded battleground for two others: central thermal plants vs. micropower, and megawatts vs. negawatts. For example, the U.S. added more windpower capacity in 2007 than it added coal-fired capacity in the past five years combined. By beating all central thermal plants, micropower and negawatts together provide about half the world's new electrical services. Micropower alone now provides a sixth of the world's electricity, and from a sixth to more than half of all electricity in twelve industrial countries (the U.S. lags with 4 percent).

In this broader competitive landscape, high carbon prices or taxes can't save nuclear power from its fate. If nuclear did compete only with coal, then far-above-market carbon prices might save it; but coal isn't the competitor to beat. Higher carbon prices will advantage all other zero-carbon resources—renewables, recovered-heat cogeneration, and negawatts—as much as nuclear, and will partly advantage fossil-fueled but low-carbon cogeneration as well.

Small Is Fast, Low-Risk, and High in Total Potential

Small, quickly built units are faster to deploy for a given total effect than a few big, slowly built units. Widely accessible choices that sell like cellphones and PCs can add up to more, sooner, than ponderous plants that get built like cathedrals. And small units are much easier to match to the many small pieces of electrical demand. Even a multi-megawatt wind turbine can be built so quickly that the U.S. will probably have a hundred billion watts of them installed before it gets its first one billion watts of new nuclear capacity, if any.

Small, quickly built units also have far lower financial risks than big, slow ones. This gain in financial economics is the tip of a very large iceberg: micropower's more than 200 different kinds of hidden financial and technical benefits can make it about ten times more valuable (www.smallisprofitable.org) than implied by current prices or by the cost comparisons above. Most of the same benefits apply to negawatts as well.

Despite their small individual size, micropower generators and electrical savings are already adding up to huge totals. Indeed, over decades, negawatts and micropower can shoulder the entire burden of powering the economy. The Electric Power Research Institute (EPRI), the utilities' think-tank, has calculated the U.S. negawatt potential (cheaper than just running an existing nuclear plant and delivering its output) to be two to three times nuclear power's 19 percent share of the U.S. electricity market; RMI's more detailed analysis found even more. Cogeneration in factories can make as much U.S. electricity as nuclear does, plus more in buildings, which use 69 percent of U.S. electricity. Windpower at acceptable U.S. sites can cost-effectively produce at least twice the nation's total electricity use, and other renewables can make even more without significant land-use, variability, or other constraints. Thus just cogeneration, windpower, and efficient use—all profitable—can displace nuclear's current U.S. output roughly 14 times over.

Nuclear power, with its decade-long project cycles, difficult siting, and (above all) unattractiveness to private capital, simply cannot compete. In 2006, for example, it added less global capacity than photovoltaics did, or a tenth as much as windpower added, or 30–41 times less than micropower added. Renewables other than big hydro dams won $56 billion of private risk capital; nuclear, as usual, got zero. China's distributed renewable capacity reached seven times its nuclear capacity and grew seven times faster. And in 2007, China, Spain, and the U.S. each added more windpower capacity than the world added nuclear capacity. The nuclear industry does trumpet its growth, yet micropower is bigger and growing 18 times faster.

Security Risks

President Bush rightly identifies the spread of nuclear weapons as the gravest threat to America. Yet that proliferation is largely driven and greatly facilitated by nuclear power's flow of materials, equipment, skills, and knowledge, all hidden behind its innocent-looking civilian disguise. (Reprocessing nuclear fuel, which the President hopes to revive, greatly complicates waste management, increases cost, and boosts proliferation.) Yet acknowledging nuclear power's market failure and moving on to secure, least-cost energy options for global development would unmask and penalize proliferators by making bomb ingredients harder to get, more conspicuous to try to get, and politically costlier to be caught trying to get. This would make proliferation far more difficult, and easier to detect in time by focusing scarce intelligence resources on needles, not haystacks.

Nuclear power has other unique challenges too, such as long-lived radioactive wastes, potential for catastrophic accidents, and vulnerability to terrorist attacks. But in a market economy, the technology couldn't proceed even if it lacked those issues, so we needn't consider them here.

Conclusion

So why do otherwise well-informed people still consider nuclear power a key element of a sound climate strategy? Not because that belief can withstand analytic scrutiny. Rather, it seems, because of a superficially attractive story, an immensely powerful and effective lobby, a new generation who forgot or never knew why nuclear power failed previously (almost nothing has changed), sympathetic leaders of nearly all main governments, deeply rooted habits and rules that favor giant power plants over distributed solutions and enlarged supply over efficient use, the market winners' absence from many official databases (which often count only big plants owned by utilities), and lazy reporting by an unduly credulous press.

Isn't it time we forgot about nuclear power? Informed capitalists have. Politicians and pundits should too. After more than half a century of devoted effort and a half-trillion dollars of public subsidies, nuclear power still can't make its way in the market. If we accept that unequivocal verdict, we can at last get on with the best buys first: proven and ample ways to save more carbon per dollar, faster, more surely, more securely, and with wider consensus. As often before, the biggest key to a sound climate and security strategy is to take market economics seriously.

Mr. Lovins, a physicist, is cofounder, Chairman, and Chief Scientist of Rocky Mountain Institute, where Mr. Sheikh is a Research Analyst and Dr. Markevich is a Vice President. Mr. Lovins has consulted for scores of electric utilities, many of them nuclear operators.

The authors are grateful to their colleague Dr. Joel Swisher PE for insightful comments and to many cited and uncited sources for research help. A technical paper preprinted for the September 2008 Ambio *(Royal Swedish Academy of Sciences) supports this summary with full details and documentation (www.rmi.org/sitepages/pid257.php#E08-01). RMI's annual compilation of global micropower data from industrial and governmental sources has been updated through 2006, and in many cases through 2007, at www.rmi.org/sitepages/pid256.php#E05-04.*

Notes:

1. This is conservatively used as the basis for all comparisons in this article
2. All monetary values in this article are in 2007 U.S. dollars. All values are approximate and representative of the respective U.S. technologies in 2007. Capital and operating costs are levelized over the lifespan of the capital investment.
3. Distributed generators may rely on the power grid for emergency backup power, but such backup capacity, being rarely used, doesn't require a marginal expansion of grid capacity, as does the construction of new centralized power plants. Indeed, in ordinary operation, diversified distributed generators free up grid capacity for other users.
4. Solar power is not included in Figure 1 because the delivered cost of solar electricity varies greatly by installation type and financing method. As shown in Figure 4, photovoltaics are currently one of the smaller sources of renewable electricity, and solar thermal power generation is even smaller.
5. A similar credit for displaced boiler fuel can even enable this technology to produce electricity at negative net cost. The graph conservatively omits such credit (which is very site-specific) and shows a typical positive selling price.
6. We ignore here the modest and broadly comparable amounts of energy needed to build any kind of electric generator, as well as possible long-run energy use for nuclear waste management or for extracting uranium from low-grade sources.
7. Since its recovered heat displaces boiler fuel, cogeneration displaces more carbon emissions per kilowatt-hour than a large gas-fired power plant does.
8. However, at long-run gas prices below those assumed here (a levelized 2007-$ cost of $7.72 per million BTU) and at today's high nuclear costs, the combined-cycle plants may save more carbon per dollar than nuclear plants do. This may also be true even at the prices assumed here, if one properly counts combined-cycle plants' ability to load-follow, thus complementing and enabling cleaner, cheaper variable renewable resources like windpower.
9. Data for decentralized gas turbines and diesel generators exclude generators of less than 1 megawatt capacity.