Mighty mice

The most powerful force resisting new nuclear may be a legion of small, fast and simple microgeneration and efficiency projects. **By Amory B Lovins**

Two men on a wild and barren plain suddenly spy a huge bear charging towards them. One man immediately starts putting on his running shoes. "How futile!" the other exclaims, "you'll never outrun that bear!" His companion drily replies: "I don't need to outrun the bear."

In any race, it's vital to understand whom you need to outrun and what it takes to win. Yet an incomplete picture of the competitive landscape may be the nuclear industry's greatest impediment to sound strategic planning, profitable investment, and credible public discourse.

This knowledge gap is understandable because the industry has been working so hard to achieve impressive progress in so many areas at once: operational consistency and reliability, simpler and cheaper designs, better inherent safety, streamlined siting and approvals, stronger government support, and other prerequisites for nuclear revival. But while these demanding tasks have taken so much attention, our bear has gained speed, approaching from behind.

Steve Kidd, the World Nuclear Association's head of strategy and research, asked in *NEI* (September 2005): "How can new nuclear power plants be financed?" He predicted this would "prove very challenging" in the private capital market, even though several studies found circumstances in which new nuclear build could compete with "building gas- or coal-powered generating capacity of similar magnitude." Investors, he suggested, remain concerned about public opposition, siting and licensing, quick construction at predictable cost, safety, security, liability, nonproliferation, waste, decommissioning, and smooth operation. And he felt nuclear power's economic merits would emerge if we had "power markets where different technologies can compete on a level playing field and where long-term investment in capacity is incentivised."

These issues remain important and challenging, yet the market reality is even more complex. Resolving all perceived risks wouldn't ensure nuclear power's market success. Rather, new nuclear plants and central coal- or gas-fired power plants are all uncompetitive with three other options whose status, prospects and value propositions are not well understood within the nuclear industry: certain decentralised renewables, combined-heat-and-power (CHP), and efficient end-use of electricity. In a rapidly evolving energy marketplace full of disruptive technologies, nuclear power's biggest challenges are not political but economic.

Most nuclear advocates consider the various 'micropower' and 'negawatt' (electricity saving) alternatives necessary and desirable but relatively small, slow, immature, uncertain, and futuristic – complementing central thermal stations without threatening their primacy. In this view, nuclear power will predominate within a balanced low-carbon electricity mix, and generation will remain overwhelmingly centralised, because nothing smaller could scale up enough to power a growing global economy. As the WNA website states: "Only nuclear power offers clean, environmentally friendly energy on a massive scale." Yet this view is hard to reconcile with recently compiled industry data.

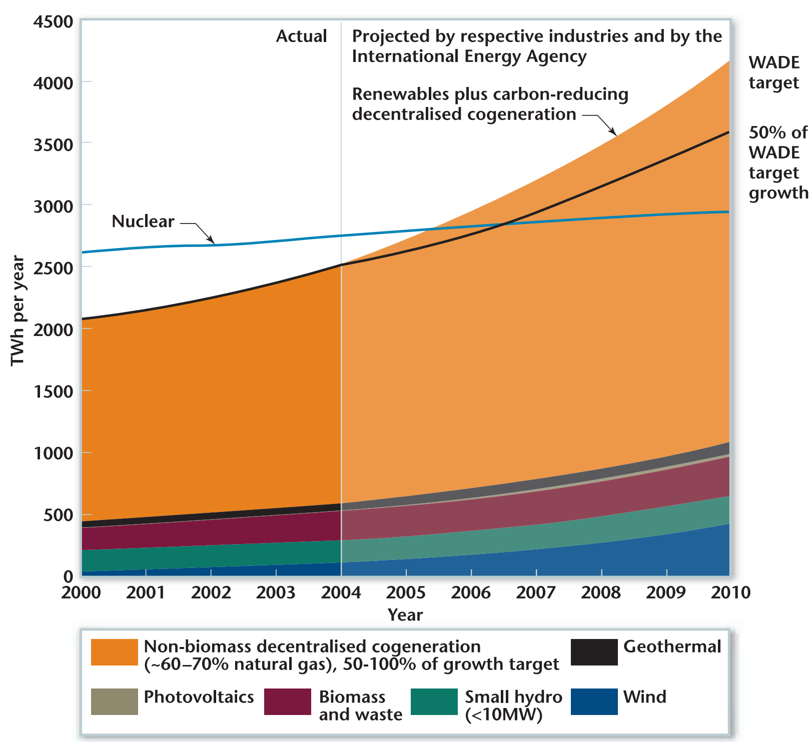


Figure 1: Worldwide electrical output of decentralised low- or no-carbon generators (except large hydro)

DECENTRALISED COMPETITORS

The World Alliance for Decentralised Energy's (WADE's) March 2005 compilation from industry equipment sales and project data estimated that decentralised resources in 2004 generated 52% of the electricity in Denmark, 39% in The Netherlands, 37% in Finland, 31% in Russia, 18% in Germany, 16% in Japan, 16% in Poland, 15% in China, 14% in Portugal, and 11% in Canada. WADE's definition includes CHP gas turbines up to 120MWe, CHP engines up to 30MWe, CHP steam turbines only in China, windpower and photovoltaics (PVs), but no hydropower, no other renewables, no generators below 1MWe, and no end-use efficiency.

Figure 1 shows the annual output of

low- and no-carbon micropower compared with nuclear power. No hydroelectric dams over 10MWe are included. Average nuclear capacity factor (load factor) is assumed to rise linearly from 84.1% in 1982 to 88.5% in 2010. Up- and downratings, new units commissioned, and permanent retirements are shown consistently for all technologies.

This data shows that micropower has already eclipsed nuclear power in the global marketplace ~~already.~~ About 65% of micropower's capacity and 77% of its output in 2004 was fossil-fuelled CHP, which was about two-thirds gas-fired, and emitted 30% to 80% less carbon (averaging at least 50% less) than the separate power plants and boilers or furnaces it replaced. The rest of the micropower was diverse renewables, whose operation, like nuclear power's (neglecting enrichment), releases no fossil-fuel carbon. Micropower's output lags its capacity by three years due to typically lower capacity factors for small hydro (~46%), windpower (~25-40%) and PVs (~17%) than for CHP (~83%), biofuelled generation (~70%) and geothermal (~75%).

Worldwide, low- and no-carbon decentralised generators surpassed nuclear power's total installed capacity in 2002 and its annual output in 2005. In 2004 they added 5.9 times as much net capacity and 2.9 times as much annual output as nuclear power. The respective industries project that in 2010, micropower will add 136-184 times as much capacity as nuclear power will add, depending on CHP, wind and PV estimates (see Figure 2). Such projections are quite uncertain, but qualitatively clear. After 2010, whether the ageing reactor fleet declines as projected by Schneider and Froggatt (see *NEI* June 2005, p36) or more slowly as predicted by the International Energy Agency (IEA), even with major new nuclear build in countries like China, micropower will continue to pull ahead.

Figure 2 shows net capacity added by each technology in each year since 1990. Figure 2 also includes a leading indicator for nuclear power: construction starts through 2004. Their unknown size thereafter shouldn't materially affect 2010 completions. In 2004, windpower just in Germany and Spain added 2GWe each, matching the average global net addition of

Comparative cost

The standard studies to which Steve Kidd referred (MIT, University of Chicago, IAEA, OECD, amongst others) all compare only the busbar costs of central stations – nuclear, coal, and combined-cycle gas. The assumptions and findings of MIT's 2003 analysis, *The Future of Nuclear Power*, are adopted here. However, to compare central stations (or remote windpower) fairly with onsite CHP and efficiency one must add to the former a delivery cost, conservatively assumed here to be $0.0275/kWh – the 1996 embedded average for US investor-owned utilities.

The MIT study found that a new 1GWe advanced LWR with a 40-year life, 85% capacity factor and merchant financing has a busbar cost of $0.0702/kWh (in 2004$), equivalent to $0.0977/kWh delivered. If its capital cost fell by 25% (from $2094/kWe to $1570/kWe overnight cost, compared to ~$2200/kWe for the new Finnish plant, an apparent loss-leader), its construction time fell from five to four years, the capital market attached zero nuclear risk premium and fuel plus O&M cost dropped from $0.0157 to $0.0136/kWh (the lowest-quartile recent US value), the delivered cost could decrease to as little as $0.0715/kWh.

Imposing a high price on carbon emissions ($100/t CO_2) could raise the nominal cost of new delivered coal power from $0.072/kWh to $0.097/kWh (burning $1.33/GJ coal), and that of new combined-cycle gas power from $0.067-0.086/kWh to $0.078-0.098/kWh (at a levelised gas price of $3.6-7.6/GJ, equivalent to escalating those initial constant-$ gas prices at 5% *pa*). Figure 3 shows how these changes could shift the central plants' relative costs.

However, the standard studies ignore decentralised competitors, perhaps in the erroneous belief they're too small or slow to matter. Let's consider three kinds. (There are more, notably the diverse non-windpower renewables whose observed uptake bespeaks economic merit, but to avoid complex site-specific comparisons, and because windpower's siting and intermittence make it a difficult case, let's use it as a surrogate for all decentralised renewables).

Lawrence Berkeley National Laboratory reported in August 2005 that more than 2.7GWe of US windpower projects installed during 1999-2005 had busbar costs, including PTC, ranging from $0.015 to $0.058/kWh (excluding one outlier), with a capacity-weighted average of $0.0337/kWh. Western US utilities' resource plans use levelised costs as low as $0.023/kWh, and the lowest 2003 nonfirm wind energy contract price was $0.029/kWh, but we conservatively assume $0.030-0.035/kWh. The 2005 spike in wind turbine prices, 25-50% above 2003's, appears to reflect temporary imbalances: spot shortages that have filled all makers' books through 2006 are due largely to PTC-related postponement of US projects from 2004 to 2005-6, whilst high steel prices will also boost central-station costs. On the contrary, industry and government expect windpower's costs to fall by ~$0.01/kWh during 2003-12 – more than the $0.0086/kWh levelised post-tax value of the PTC. For illustration, Figure 3 optionally adds back windpower's PTC but not the pre-2005 subsidies received by central stations, especially nuclear power. Those nuclear subsidies are complex, diverse and disputed but the most authoritative independent US expert, Doug Koplow, estimates ~$0.0079-0.0422/kWh, increased by another ~$0.034-0.040/kWh in the Energy Policy Act of 2005 for at least the next 6GWe ordered.

For comparability with central stations, we assume that making windpower fully dispatchable costs $0.009/kWh – two-thirds for hydroelectric or other firming, one-third for grid integration. We conservatively adopt that extra cost, higher than most western US utilities pay or assume, partly in case some remote sites need extra transmission.

Conversely, central stations are assumed to incur no reserve-margin nor spinning-reserve costs, though their larger unit sizes make them tend to fail in larger chunks and for longer. Intermittence does need attention and sound engineering, but it's not unique to renewables: every source of electricity is intermittent, differing only in why they fail, how often, how big, how long, and how predictably. Grid operators' recent assessments confirm that windpower's intermittence even at high penetrations – about 14% for Germany, 20-25% for several US grids, and 30% for west Denmark – would be manageable at modest cost, typically a few $/MWh, if renewables are properly diversified, dispersed, forecasted, and integrated with the existing grid and with demand response.

The WNA's latest (February 2005) renewables webpage disagrees: it ignores technological and siting diversity and demand response. The WNA therefore concludes that intermittent renewables "cannot directly be applied as economic substitutes for coal or nuclear power" and will require "reliable duplicate sources of electricity, or some [unavailable] means of electricity storage on a large scale" – "almost 100%" backup – raising windpower's cost to twice the "generation cost" of nuclear or coal.

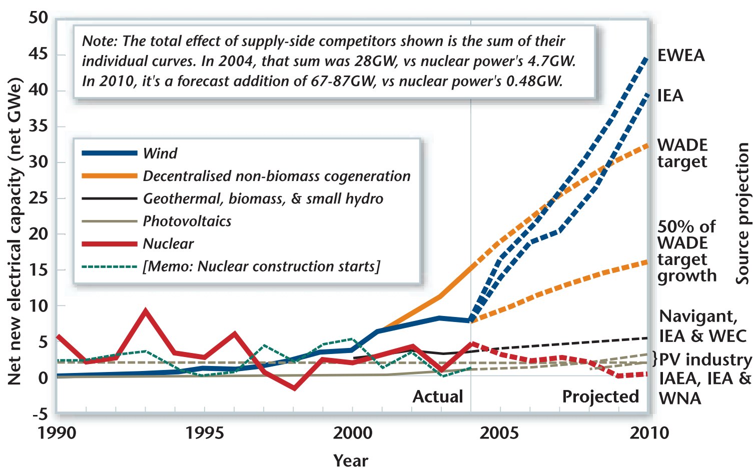
Highly intermittent supplies were long assumed to be limited to 5-10% of grid capacity, then 20%; the WNA claims 10-20%. Yet with better forecasting, grid integration, distribution automation and smart power electronics such supposed limits continue to recede. Windpower penetrations today are 20% in Denmark and up to 30% in three German states. On windy, light-load days in certain regions of Denmark, Germany, and Spain, windpower can exceed 100% of load, foreseeably and manageably. Yet windpower's grid integration costs are proving negligible or very modest. The corresponding costs of integrating other resources, all with nonzero forced outage rates, are of course already borne unnoticed. Nor are "reliable duplicate sources" proposed for nuclear plants, which in 2003 suffered prolonged large-scale curtailments in Europe's heatwave, restart after the USA/Canada blackout and Tokyo Electric's safety shutdown.

CHP is a far more conventional and reliable resource already common in many countries. Figure 3 shows US costs for three arrangements, the first two based on actual projects by a leading US developer, Primary Energy, with 0.9GWe of operating projects. Conventional gas-fired combined-cycle industrial CHP – with levelised gas prices of $5.4-8.7/GJ, a 10% pa return over 25 years, and unit sizes of 28-64MWe – delivers new electricity for $0.038-0.073/kWh. Recovered industrial heat previously wasted can be worth more than CHP's other operating and capital costs, making its net cost of delivered electricity negative (-$0.021 to -$0.047/kWh) in the three 60-160MWe projects evaluated. We graph instead their positive all-in electricity price ($0.011-$0.026/kWh), with the possibility of costs up to ~$0.04/kWh in less favourable cases. Well-integrated into a commercial building and with demand-side management, gas-fired 'trigeneration' of power, heat, cooling, and perhaps other services can deliver electricity at a net cost around $0.01-0.03/kWh, or up to about $0.07/kWh with sub-optimised designs.

The final major competitor shown in Figure 3 is efficient end-use of electricity. Carefully evaluated programmes of many US utilities have yielded reliable, durable, and accurately predicted savings at societal costs ~$0.01/kWh or less in commercial and industrial retrofits. Less optimised programmes or those emphasising homes can incur average costs up to ~$0.03-0.05/kWh. Alternatively, integrative design techniques well demonstrated in many buildings and industrial sectors often achieve very large savings at reduced capital cost, hence at a negative 'cost of saved energy' (investment divided by the discounted stream of lifetime electricity savings).

See www.rmi.org/sitepages/pid171.php#E05-08 for documention.

Figure 2: Global additions of electrical generating capacity by year and technology



nuclear capacity *per annum* (*pa*) during 2000-10. Worldwide nuclear construction starts will soon probably add fewer GWe *pa* than PV installations.

These comparisons omit another key decentralised competitor – saved electricity – that is seldom properly tracked but clearly substantial. At constant capacity factor, the 2.0% and 2.3% decreases in US electricity consumed per dollar of GDP during 2003 and 2004 would respectively correspond to saving 14 and more than 16 peak GWe, plus 1GWe *pa* of utility load management resources added and used. That's 6-8 times US utilities' declared 2.2GWe of peak savings achieved in 2003 by demand-side management. Since the USA uses only one-quarter of global electricity, and more efficient end-use is a global trend, worldwide electrical savings almost certainly exceed global additions of micropower (24GWe in 2003, 28GWe in 2004). Global additions of supply-side plus demand-side decentralised electrical resources are thus already an order of magnitude larger than global net additions of nuclear capacity (4.7GWe in 2004).

Few investors and policymakers realise this, because most official statistics under-report decentralised and non-utility-owned resources, show only physical energy supply, and pay little attention to drops in energy intensity, whatever their cause (in most countries, chiefly more efficient end-use technologies). Per dollar of GDP, US primary energy consumption has lately been falling by about 2.5% *pa*; electricity by 2.0% *pa*. Only 22% of the 1996-2005 increase in delivered US energy services was fuelled by increased energy supply, 78% by reduced intensity – yet the latter four-fifths of market activity remains dangerously invisible.

That invisibility lately led US merchant firms to lose ~$100 billion by building ~200GWe of combined-cycle gas plants for which there was no demand.

This calamity for investors could soon recur on a larger scale and not only in the power sector. The US Energy Policy Act of 2005 greatly increased subsidies and regulatory aid for energy supply whilst largely ignoring demand-side resources. Yet 'negawatts' expand as energy prices rise, and as policies that have held per-capita electricity use flat for 30 years in California and are decreasing it in Vermont spread to other US states.

Like micropower, efficiency tends to be installed more quickly than supplies. If it continues to reach customers and grab revenues first, it will glut markets, crash prices, and bankrupt producers, just as it did under similar conditions in the mid-1980s. This would intensify investors' risk aversion.

Many factors tug energy outcomes in diverse directions. Windpower, for example, is heavily subsidised in the UK where it has yet been slowed onshore by local opposition, and offshore by two years' government debate on how to finance its links to the grid. Similarly, US windpower gets a production tax credit (PTC) but its erratic and brief renewals by Congress have repeatedly bankrupted leading wind turbine producers. Overall, the correlation between renewable installation rates and government subsidies is not clear-cut. Neither are per-kWh subsidies' relative sizes for renewables versus central plants, particularly nuclear power. Nor is it obvious whether relative subsidies are more or less important than the barriers that in most countries still block fair competition. This analytic fog makes it dangerous to assume that micropower's success is subsidy-driven, or that its obscure implementation obstacles are less important or tractable than nuclear's familiar ones.

A simpler explanation for micropower's market success might be superior basic economics. Figure 3 supports this hypothesis by comparing the cost of a kWh delivered to the retail meter from various marginal sources.

In concluding that nonhydro renewables are unsuitable "for large-scale power generation where continuous, reliable supply is needed," the WNA commits two common fallacies: supposing that making large amounts of electricity requires large generating units, and forgetting that *ceteris paribus*

Conservatisms

Decentralised resources' cost advantage (Figure 3) is robust even against implausible improvements in central stations' technology or regulation. For example, if some new sort of fission or fusion reactor could provide free steam to the turbine, the remainder of the central thermal plant would still cost too much to compete. And the cost comparisons shown have two other major conservatisms favouring central plant: they reflect a static snapshot of competitors' costs, not (save one windpower illustration) their continuing rapid decline in real cost; and they count as zero all but one (thermal integration) of the 207 'distributed benefits' described in Rocky Mountain Institute's book, *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size.* The market is increasingly counting those benefits which collectively boost value ~10-fold, enough to flip most investment decisions.

This increase in value has three separate causes, excluding such externalities as environmental and social benefits. The most important distributed benefits come from financial economics:

- **Small, fast modules incur less financial risk than big, slow projects. In a typical substation support application, this can raise the tolerable capital cost of a distributed resource, like PVs, by about 2.7-fold.**
- **Renewables avoid the financial risk of volatile fuel prices, raising windpower's typical value by about $0.01-0.02/kWh.**

These and other financial-economics benefits typically boost decentralised projects' economic value by about an order of magnitude if they're renewable, ~3-5-fold if they're not.

Better known are such electrical engineering benefits as avoided grid costs and losses, increased reliability and resilience, more graceful fault management, free reactive power control (from DC sources inverted to AC), and longer distribution equipment life (by means of reduced heating and tapchanging). Together, these typically increase value by ~2-3-fold – more if the distribution system is congested and new distribution capacity can be deferred or avoided, or if especially reliable or high-quality power is required. Finally, scores of diverse 'miscellaneous' benefits typically about redouble economic value – more if 'waste' heat can be recaptured.

many small units near customers are more reliable than fewer, bigger units far away. Central thermal stations are no longer the cheapest or most reliable source of delivered electricity, because generators now cost less than the grid and have become so reliable that 98-99% of US power failures originate in the grid. Thus the cheapest, most reliable power is typically produced at or near customers. Three-quarters of US residential and commercial customers use electricity at an average rate not exceeding 1.5 and 12kWe, respectively – severely mismatched to central plants' GWe scale. The WNA acknowledges a debate about scale, but ignores its profound implications and assumes central plants will remain dominant. Prudent investors favour micropower.

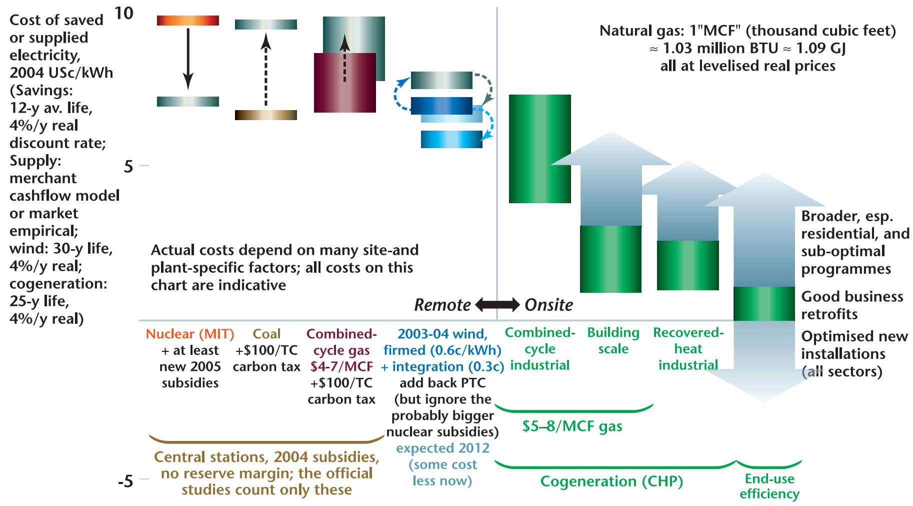


Figure 3: Nuclear power's competitors on a consistent accounting basis. Levelised cost of delivered electricity or end-use efficiency (at 2.75¢/kWh delivery cost for remote sources).

COMPARATIVE POTENTIAL

Of course, if decentralised resources had little potential to meet the world's rising needs for energy services, they'd be of minor competitive concern: one should worry about a bear, but hardly about a mouse. Yet a mighty swarm of mice is another matter. The modern literature suggests that decentralised resources' collective practical potential has been understated, as if the stunning technological and economic advances in conventional energy supply didn't apply to its rivals. To the contrary, such progress tends to be faster in decentralised resources. For example:

- At less than the delivered cost of just operating a zero-capital-cost nuclear plant (~$0.04/kWh), potential US electricity savings range from two to four times nuclear power's 20% share of the US electricity market, according to bottom-up assessments summarised by the Electric Power Research Institute (EPRI) and Rocky Mountain Institute's joint *Scientific American* article (September 1990). EPRI's Clark Gellings confirmed in 2005 that the US electric end-use efficiency resource is probably now even bigger and cheaper, because better mass-produced technologies more than offset savings already captured. Utility-specific data confirms a broad downward trend in the unit cost of 'negawatts'.
- CHP potential in industry and buildings is very large if regulators allow it. Waste-energy CHP alone is preliminarily estimated by Lawrence Berkeley National Laboratory to have a technical potential nearly as large as today's US nuclear capacity, though cost and feasibility are very site specific.
- Modern windpower's US potential on readily available rural land is at least twice national electrical usage.
- Other renewable sources of electricity are also collectively important – small hydro, biomass power (especially CHP), geothermal, ocean waves, currents, solar-thermal, and PVs. These sources and windpower also tend to be statistically complementary, working well under different weather conditions. All renewables together (excluding big hydro), plus solar technologies that indirectly displace electric loads (daylighting, solar water heating, passive heating and cooling), have a practical economic potential many times total US electricity consumption – at least an order of magnitude greater than nuclear power provides today.
- Even at such a scale, a diversified renewable portfolio needn't raise land-use concerns. For example, a rather inefficient PV array covering half of a sunny area 160×160km could meet all annual US electricity needs. In practice, since sunlight is distributed free, PVs would be integrated into building surfaces, and installed on roofs, over car parks, and along roads, both to save land and to make the power near loads. Specious claims persist comparing (say) the footprint of a nuclear reactor with the (generally miscalculated) land area of which a fraction – a few percent for wind turbines – is physically occupied by energy systems and infrastructure. In fact, total fuel cycle land use is roughly comparable for solar, coal and nuclear.

Thus renewables clearly have a very large global potential. The IEA's *World Energy Outlook 2004* foresees a 2030 renewable potential of ~30,000TWh *pa* (less than a quarter of it from hydropower). Such massive production would become far easier with CHP and efficient end-use. It still wouldn't be easy, but neither would central stations of similar output – especially for serving the two billion people not now on any grid.

COMPARATIVE SPEED

But might decentralised supply- and demand-side resources be too slow to deploy, requiring central stations to provide enough reliable power, quickly enough, to meet burgeoning demand? This widely held view seems inconsistent with observed market behaviour. As shown above, micropower and efficient end-use, despite many obstacles, are already adding an order of magnitude more GWe *pa* than nuclear power worldwide. Their brisk deployment reflects short lead times, modularity and economies of mass production (they're more like cars than cathedrals); usually-mild siting issues (except in some unusual windpower cases); and the inherently greater speed of technologies deployable by many diverse market actors without complex regulatory processes, ponderous enterprises, or unique institutions.

Of course every energy option faces specific obstacles, barriers, and hence risk of slow or no implementation at scale. Efficiency, for example, faces some 60-80 market failures, many arcane, that have left most of it unbought. Yet US electric intensity has declined at an unprecedented average rate of 1.5% *pa* since 1996 even though electricity is the form of energy most heavily subsidised, most prone to split incentives, least priced on the margin, and sold by distributors widely rewarded for selling more kWh. Such firms as DuPont and IBM routinely cut their energy intensity by 6% *pa* with attractive profits and no apparent constraints.

Letting all decentralised resources really compete risks not a dry hole but a gusher. Just during 1982-85, when California's three investor-owned utilities offered a relatively level playing field, fair competition elicited 23GWe of efficiency plus 21GWe of generation (13GWe of it actually bought) rising by 9GWe *pa*. The resulting glut, 144% of the 1984 peak load of 37GWe, forced bidding suspension in 1985, lest every fossil and nuclear plant be displaced (which in hindsight could have been valuable).

Investors appreciate that diversification is wise but must be intelligent. The strategic virtue of a diversified portfolio doesn't justify buying every technology or financial asset on offer. The sweeping claim that 'we need every energy technology' – as if we had infinite money and no need to choose – is often made but cannot withstand analysis. The WNA's website doesn't mention demand-side resources, and denies the existence of a large and compelling literature of nuclear-free, least-cost, long-term scenarios published over decades (in 1989, for example, Vattenfall published a roadmap for rapid economic growth, full nuclear phaseout, one-third power-sector CO_2 reduction, and $1 billion *pa* cheaper energy services). But investors with similarly limited vision are in for a shock. As all options compete and as increasingly competitive power markets clear, any supply investment costlier than end-use efficiency or alternative supplies risks being stranded by retreating demand.

OIL, CLIMATE, AND STRATEGY

A major argument often made for new nuclear build is oil displacement; yet this has already been largely completed. Only 3% of US electricity is made from oil and less than 2% of US oil makes electricity. Worldwide, these figures are around 7% and falling. Most of that oil, too, is residual, not distillate, and is burnt on relatively small grids by smaller plants with low capacity factors, unsuited to nuclear displacement. Both oil and fungible natural gas can be far more cheaply displaced by other means, mainly by doubled end-use efficiency.

A more compelling need is displacing coal-fired electricity to protect the earth's climate. Yet nuclear power's dubious competitive economics could make it counterproductive, for four reasons:

- Most of the carbon displacement should come from end-use efficiency, because it's profitable – cheaper than the energy it saves – and quick to deploy.
- End-use efficiency should save not just coal but also oil, particularly in transport. Comprehensive energy efficiency addresses 2.5 times as much CO_2 emission as any electricity-only initiative.
- Supply-side carbon displacements should come from a diverse portfolio of short-lead-time, mass-producible, widely applicable and accessible, benign, readily sited, rapidly deployable resources.
- The total portfolio of carbon displacements should be both fast and effective.

This last point highlights a troublesome implication of Figure 3's cost comparison. Buying a costlier option, like nuclear power, instead of a cheaper one, like 'negawatts' and micropower, displaces less carbon per dollar spent. This opportunity cost of not following the least-cost investment sequence – the order of economic and environmental priority – complicates climate protection. The indicative costs in Figure 3 (neglecting any differences in the energy embodied in manufacturing and supporting the technologies) imply that we could displace coal-fired electricity's carbon emissions by spending $0.10 to deliver any of the following:

- 1.0kWh of new nuclear electricity at its 2004 US subsidy levels and costs.
- 1.2-1.7kWh of dispatchable windpower at zero to actual 2004 US subsidies and at 2004-2012 costs.
- 0.9-1.7kWh of gas-fired industrial cogeneration or ~2.2-6.5kWh of building-scale trigeneration (both adjusted for their carbon emissions), or 2.4-8.9kWh of waste-heat cogeneration burning no incremental fossil fuel (more if credited for burning less fuel).
- From several to at least 10kWh of end-use efficiency.

The ratio of net carbon savings per dollar to that of nuclear power is the reciprocal of their relative cost, corrected for gas-fired CHP's carbon emissions (assumed here to be threefold lower than those of the coal-fired power plant and fossil-fuelled boiler displaced). As Bill Keepin and Greg Kats put it in *Energy Policy* (December 1988), based on their still-reasonable estimate that efficient use could save about seven times as much carbon per dollar as nuclear power, "every $100 invested in nuclear power would effectively release an additional tonne of carbon into the atmosphere" – so, counting that opportunity cost, "the effective carbon intensity of nuclear power is nearly six times greater than the direct carbon intensity of coal fired power." Whatever the exact ratio, their finding remains qualitatively robust even if nuclear power becomes far cheaper and its competitors don't.

Speed matters too: if nuclear investments are also inherently slower to deploy, as market behaviour indicates, then they don't only reduce but also retard carbon displacement. If climate matters, we must invest judiciously, not indiscriminately, to procure the most climate solution per dollar and per year. Empirically, on both criteria, nuclear power seems less effective than other abundant options on offer. The case for new nuclear build as a means of climate protection thus requires reexamination.

Micropower and its natural partner, efficient end-use, have surpassed and outpaced central stations despite many obstacles. Being diverse, ubiquitous, plentiful, widely available, largely benign, and popular, they are also hard to stop. To be sure, much work remains to purge the artificial barriers to true competition between all ways to save or produce energy, regardless of which kind they are, what technology or fuel they use, how big they are, or who owns them. But such a free market, for which Kidd rightly calls, seems increasingly unlikely to favour nuclear power. Rather, the economic fundamentals of distributed resources promise an ever-faster shift to very efficient end-use combined with diverse generators the right size for their task. That shift could render insufficient or even irrelevant the resolution of the perceived non-economic risks that preoccupy the nuclear industry.

The better the industry and its investors understand this, the more likely they are to fulfil reasonable expectations, apply their talents effectively, and help achieve the global energy, development, and security goals to which we all aspire.

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