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Working Papers For Keeping The Lights On

Generating Change
Working Paper 2

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Why generate electricity? The question seems absurd. Electricity keeps the lights on, and makes possible countless other services. Those of us in the fortunate parts of the world take electricity and its uses completely for granted. Refine the question, however, and it takes on surprising urgency, at least for some of those involved. Why generate electricity in this way, in this form? Is this way the best way? Is this form the best form, given what we expect of electricity, and the opportunities now available? A decade or so ago these questions too would have looked absurd. Now the answers are anything but obvious. We are no longer certain which technologies to choose to generate, deliver and use electricity, or where to install them, under what ownership or control. Indeed we no longer know who should decide, or how. We have begun to break away from traditional electricity, and from the centralized monopoly franchise with captive customers; but we have yet to find a wholly satisfactory alternative. Electricity business used to be unchanging, even boring, safe enough for widows and orphans. It has now become almost as nerve-racking as bungee-jumping.

The cumulative impact of so much uncertainty raises an immediate corollary. If we were starting now, with no preconditions, knowing what we now know, to design a system to generate and use electricity, it would almost certainly look more or less different from all the systems we actually have. In particular it would look distinctly different from the central-station synchronized alternating current system, replicated over much of the world in the previous century. Yet this type of system now includes some 3000 gigawatts of generating capacity, and has served billions of electricity users well for nearly half a century. It may no longer be the best we can do, or even good enough; but it has demonstrated unequivocally the remarkable utility and versatility of electricity and the services it delivers. People all over the world rely on it. For those without it - two billion people, one-third of humanity - life is more difficult, often much more. What happens to electricity, to the systems we already have and to those we need, will be crucial for the future of sustainable development around the world.

How may existing electricity systems change, and why? What may new systems be like, and why? The answers to these questions will have sweeping implications for technical configurations, financial arrangements, institutional frameworks and business relationships. This Working Paper will focus on one aspect of the electricity process: generating and generating change. Working Paper 3 will focus on networking and networking change. However, while subdividing the issues for separate consideration, each Working Paper will stress the underlying unity of the electricity process and the system within which it takes place.

To understand change that may happen, start by revisiting change that has happened already. The transition now underway shows some intriguing parallels with the transition that took place in the early decades of electricity. Then, as now, the issues for generation included choice of technology; cost; size; location; ownership; connection to networks; source of revenue; and planning constraints. Many of the criteria then invoked are still in use - no longer always defensibly. Indeed the most dramatic changes in electricity systems happened more than a century ago, between the 1870s and the 1890s. In the 1870s, an entrepreneur such as Thomas Edison sold complete systems, for electric arc lighting. A purchaser took title to all the assets - generator, cables, controls, arc-lamps - all of which were installed on the purchaser's site. The owner was then responsible for operating and maintaining the whole system - that is, for keeping his own lights on. In 1882, using his new incandescent lamp, Edison established his first central-station systems, in Holborn, London, and then in the Wall Street district of lower Manhattan. At the outset Edison retained title to all the assets, and charged his customers according to how many lamps they used; he was selling illumination - the service delivered by the complete electricity system. By the mid-1880s, however, the first practical electricity meter became available, to measure the flow of electricity through a circuit. Within a very short time Edison, his competitors, and other electric entrepreneurs in North America, Europe, Japan and farther afield, were selling not arc-lighting systems nor incandescent light but electricity - the process - measured and priced by the unit.

The key reason for this rapid change in the nature of the electricity business, and the relationship between suppliers and customers, was the cost of generating electricity, and the possibilities then available to reduce this cost. Not surprisingly, that has remained a determining factor in the evolution of electricity ever since. In the 1870s, those interested in using electricity had to choose between the two available practical options for generation, the battery or the dynamo. Telegraph companies used batteries, because they could be sited where needed and readily replaced, and because the system did not require large flows of electric current. Arc light, however, required a substantial current; to provide it with batteries would be expensive and inconvenient. The dynamo could deliver a much larger current continuously with comparative ease; but it had to be turned by a 'prime mover' - a source of kinetic energy to be converted into electrical energy. Suitable prime movers available in the 1870s were of two kinds, typified by the water wheel and the steam engine. A water wheel could use the energy from a flow of water, a stream or waterfall, that was effectively free of charge; but the wheel, and the dynamo it turned, had to be sited where the water was - not necessarily close to where the user wanted the light. A steam engine, on the other hand, could be sited anywhere, provided it had access to a supply of fuel, almost invariably coal. With a steam engine and dynamo a user could have light essentially anywhere - anywhere, that is, that the noise, smoke and ash from the generator could be tolerated. The user however had to buy and pay for the coal required to generate the electricity.

These two forms of generation, using water power and steam power, typified a dichotomy that persists into the twenty-first century, whose significance for the future of world electricity may steadily increase. Generation using water power, or 'hydroelectricity', uses an array of physical assets to convert a flow of natural ambient energy, that of falling water, into electricity. The water flow is a natural phenomenon, delivered by and dependent on rain and topography, continuing whether or not any of the flow is used to turn a rotating machine to generate electricity. The cost of electricity from this kind of generation is determined almost completely by the investment cost of the physical infrastructure that converts water-energy to electrical energy. By contrast, generation using steam power requires fuel to raise the steam. The cost of the fuel may represent a substantial fraction of the total cost of the electricity produced. The distinction between such fuel-based generation and 'infrastructure generation' that does not require fuel - including not only hydroelectricity but wind power, wave power, tidal power and photovoltaics - has not hitherto been adequately recognized. The corollary implications, not least for the finances, the risks, and the environmental impact of electricity, demand much closer scrutiny. A subsequent section of this Working Paper will examine such implications.

In the early decades of electricity, both water-powered and steam-powered generation, while differing markedly in other respects, shared one crucial attribute: economy of unit scale. Water-wheels and water-turbines, steam engines and steam turbines, dynamos and alternators all exhibited this desirable feature: a larger unit produced cheaper electricity. This indeed was the reason why Edison and his contemporaries pursued the concept of central-station generation and extended network distribution of electricity. Only by increasing the size of the generator could the cost of electric light be made competitive with that of gas light from town gas. Such a large generator would produce more electricity than could be used on a single site - hence the need for a network through public space to customers on other sites. But the cost-savings on a larger generator would more than make up for the extra cost of the extended network. The entire concept and configuration of central-station electric light was in fact based directly on the long-since successful model of central-station gas light, and for much the same reasons, primarily economy of scale of production.

One major difference however arose. Town gas was a physical commodity. Produced by roasting coal in large retorts, town gas could be stored, in huge expanding tanks that served as a buffer between the retorts and the users of the gas. Although people wanted illumination mainly in the hours of darkness, the retorts could operate continuously at maximum output, filling the tanks during the daytime to help meet the load at night. Electricity, however, was not a commodity but a physical process, happening simultaneously and instantaneously throughout the entire interconnected system. Unlike gas, electricity could not be stored. It had to be generated essentially at the instant it was used. The system therefore had to have enough generation available to meet the maximum load on the system. For most of the day, however, this generation would operate below its maximum output or even stand idle.

For a self-contained arc-lighting system, this was not really an issue. The owner-operator simply switched on the generator when wanting light, exactly as one still does with a hand-held electric torch or flashlight. The owner accepted the cost of having the generator and the rest of the system idle for much of the time, as a corollary of having it available when wanted. The owner did not measure the flow of electricity, much less pay for it by the unit. For the operator of a central-station system, however, installing and operating generation able to meet the maximum load was an investment that had to be recouped from customers. But charges had to be kept down; customers unhappy with the cost of electric light might revert to gas light. On the other hand, generation operating below capacity was earning less revenue; if it were standing idle it was earning none at all, though capital charges had still to be paid.

The mismatch between maximum load and maximum generation, such a headache for early electric entrepreneurs, is an inevitable concomitant of breaking the continuity of the electricity process - of treating electricity as a quasi-commodity and selling it by the measured unit. The customer purchases electricity by turning on a switch, and expects the electricity to be delivered essentially instantaneously. The system must respond accordingly, increasing generation to match the increased load. According to this arrangement, the loads are ready and waiting to be connected to the system whenever the independent owners of the loads so desire. The system in turn must have generation ready and waiting to respond. This state of affairs, the fundamental tenet of the traditional central-station electricity system, has prevailed for so long that it feels sacrosanct. It need not be, as this Working Paper will later discuss.

Edison, his contemporaries and their successors tackled the problem in three ways: expanding systems, adding new types of load, and interconnection. Increasing the size of the system, by adding more customers and more loads, justified installation of ever larger generators; the consequent economies of scale steadily lowered the cost of generating electricity. If the loads could be added on premises already connected, avoiding the need to expand networks, so much the better. Introducing a different type of load, the electric motor, began to build a user-base for electricity during the daylight hours when few lights were on. Edison's systems were based on direct current (DC), comparatively simple technology, but with some severe limitations. Nicola Tesla and George Westinghouse pioneered the generation and use of alternating current (AC), the transformer and the AC motor. The advent of AC dramatically expanded technical opportunities. Then, gradually, as more generators were added and delivery networks expanded, the possibility of interconnecting systems became feasible and attractive. Working Paper 3 will consider the network implications of interconnection, then, now and in the future. For generation, interconnection meant reducing the maximum capacity required to allow for faults or failures at times of maximum load. Moreover, if systems had differing proportions of motors or lighting, differing 'load profiles', linking the systems improved the overall utilization of total generation. From the 1890s onwards the so-called 'load factor' became a major concern - the actual use of system generation, as a fraction of its potential maximum output. Since revenue depended on the number of units of electricity sold, load factor became a key indicator of return on system assets.

In the early years, when systems were still small, skewed load profiles led to low load factors and seriously hampered economic performance. Electric entrepreneurs embarked on a process that continued for decades, called 'load-building', intended not only to increase the total use of electricity, and the generation needed to provide it, but more particularly to increase the use of electricity in daylight hours, to balance the lighting load in the evening and nighttime. Load-building had another corollary, less obvious. The use, and the uses, of electricity expanded into more and more aspects of daily life. Applications once confined mainly to industry, especially motors, became ever more common in households. Electricity use on weekends steadily increased. Society began to regard electricity - not just electricity but specifically electricity generated in central stations and delivered over a network - not as a luxury but as an essential.

That set the stage for a crucial step in the evolution of electricity systems: the establishment of the monopoly franchise. Within such a franchise area no one but the franchised monopoly can generate electricity for sale. Until the 1920s, central-station generators had to compete with not only with gas for lighting but also with on-site and other local electricity generation, notably by tram companies and factories. But central-station proponents such as Samuel Insull of Commonwealth Edison in Chicago, along with many others, lobbied politicians relentlessly, claiming that an electricity system was a 'natural monopoly'. At length the relevant politicians in country after country agreed. With the monopoly franchise area no one but the franchise holder was allowed to generate electricity for sale. Users could generate their own, but could not sell any surplus; and those wanting to buy electricity had to take it from the monopoly supplier, on terms decreed by some regulatory authority appointed by the relevant government.

The monopoly franchise, fostering ever-larger generating units, gave the central-station system an advantage that slowly, inexorably suffocated on-site generation. In urban areas local generators shut down their own plants and began to buy their electricity from the monopoly system. In rural areas such as the midwestern states and provinces of North America and outlying areas of Scotland, a brief burgeoning of small-scale privately-owned on-site wind generation was snuffed out by monopoly systems extending lightly-loaded networks massively subsidized by taxpayers. Natural or not, the monopoly franchise became an established political reality, to be taken for granted for more than half a century.

From the 1920s onwards the monopoly franchise, under some form of government regulation, became the basis of electricity systems around the world. It remained so until the late 1980s and the advent of liberalization. Even after liberalization, networks have usually remained monopolies, not always for good reason, as Working Paper 3 will discuss. For generation, the monopoly franchise, with its captive customers, removed the risk associated with investing in larger and more long-term generation projects. In principle, such larger generators were expected to produce cheaper electricity. But even if they did not, the captive customers would pay. The result was a steady increase in the unit size of individual generators and of the central stations housing them. From the 1950s through the 1980s the scale-up was relentless.

As steam-cycle materials and engineering steadily improved, fuel-based generation gradually overtook and then outstripped hydro generation. Coal remained the dominant fuel for raising steam. However, as oil refineries sprang up to service the expanding population of internal combustion engines, heavy residual oil became both abundant and cheap; many large generating stations burning heavy resid were built as adjuncts to refineries. Natural gas, a troublesome accompaniment emerging from some oil wells, also became available as a fuel to raise steam, if a nearby network connection could justify investing in a generator rather than simply flaring the gas to get rid of it - and if the monopoly system would accept the electricity. A yet more exotic way to raise steam also became available, with vigorous promotion and financing from national governments - nuclear reactors in nuclear power stations.

Units became so large that major turboalternators had to be kept turning at the network frequency, 'synchronized' but delivering no power, as so-called 'spinning reserve', ready to take over in seconds if an operating unit should fail. Maintaining the stability of vast and intricate alternating-current networks required a whole catalogue of such so-called 'ancillary services', as Working Paper 3 will discuss. On traditional monopoly systems generators delivered these ancillary services as a matter of course, as part of the centralized operating regime. The additional costs to generators of providing the ancillary services went largely unrecognized.

By the 1960s the range of options for generation, especially fuel-based generation, presented system planners with difficult choices. But one overriding consideration prevailed almost everywhere, right into the 1980s: no matter what mishaps, misjudgements and mistakes they suffered, the planners did not have to answer for them. The monopoly franchise saw to that. Moreover, during this time power stations had grown so large that they routinely took a decade or more to plan, build and bring into operation, by which time those initially responsible had not infrequently retired or died. Planners nevertheless continued to cite the anticipated cost of the electricity output from a new station as the guiding criterion for their choice of generating technology and fuel. For new nuclear stations, pronouncements about anticipated cost of electricity output plumbed depths of absurdity not hitherto observed.

From that time on the question of cost, as applied to electricity generation, should have attracted much more critical study than it has subsequently received. Since liberalization the comparative cost of different forms of generation has been regularly cited as the basis for decisions about generating technologies and fuels. In a liberalized context, however, those making the decision, those choosing generation in which to invest, are no longer immune from the consequences of their mistakes. They are betting their own money, and that of their shareholders and bankers. Their track record since liberalization is unimpressive, to put it mildly. Yet the catalogue of options for generation is now longer and more varied than ever before. In the new liberal context the problem is further complicated by uncertainties about network costs including connection, about electricity wholesale prices and about level of demand. Moreover, generating units on a single interconnected system may have a variety of different owners, with widely differing business agendas and reasons for owning generation. Valid selection criteria for new generating capacity, including persuasive and accurate comparative costings, have never been more necessary, nor more elusive.

Start with the ideal. What might ideal electricity generation look like? It would be imperceptible. The light would go on, the motor start, the computer function, with no visible corollary anywhere, no cost and no side-effects. Electricity itself is indeed imperceptible; but existing generation, especially traditional generation, is anything but. Generating technology costs money, often a very great deal of money, in investment and - especially for fuel-based generation - running expenses. Generators may be visually obstrusive, sometimes dramatically so. They may be noisy, smoky, and smelly, and discharge quantities of waste, gaseous, liquid and solid. They may also emit greenhouse gases, particularly carbon dioxide. At the end of their useful lives they may prove difficult to remove. Ideal electricity generation would have to eliminate all these drawbacks.

Perhaps the closest actual approximation to ideal generation might be a small hydroelectric station built, say, in the 1930s. Its capital cost is long since amortized; and it incurs no fuel cost. It requires no permanent staff and minimal maintenance. Its impact on the environment has largely been accommodated and assimilated by its surroundings. It is part of the built infrastructure; but over the decades it has become in effect part of the landscape - a part of the landscape that generates electricity. The only visible corollary of its function would be the network carrying its electricity output to loads somewhere else. If the cables were buried, the presence of the generation, and indeed of the entire electricity system for this generation, would be even more subtle. Lingering questions about the reliability, power quality and vulnerability of electricity from this generation are likely to arise more from the delivery network than from the generation itself. If the network can be shortened and simplified these residual questions dwindle almost to insignificance.

The only substantial question - admittedly non-trivial in some cases - relates to the flow of natural energy, in this case the water-flow, that drives the generator. If the flow subsides or ceases, so does the output of electricity. That is an inevitable corollary of such infrastructure generation, and an argument for interconnecting infrastructure generation of different types and locations, to minimize the circumstances in which natural energy flows may prove insufficient to provide the electricity desired.

Unfortunately, adding a new hydro station built sixty years ago is not an option. Ideal generation must remain an ideal, not a practical reality. But comparison of the ideal with the practical reality is nevertheless instructive. Could we gradually approximate to the ideal, over time, from where we are now? How might we do so? Having an ideal in mind as a long-term objective could provide a useful touchstone, and even indicate potential strategic pathways, particularly when the catalogue of potential generating options is already long and growing longer. We must however acknowledge key corollaries of any such hypothetical analysis. Before liberalization, electricity planners happily laid out schemes extending at least four decades into the future, some of the wilder nuclear schemes even longer. In liberalized electricity, however, no such central planning function any longer exists, that could even in principle implement any long-term programme of convergence toward an ideal. Moreover, individual system participants have widely differing interests and agendas, which tend to be at best medium-term, far shorter than the timescale of possible convergence toward any ideal, which will be decades, conceivably most of this new century.

These corollaries have a further profound implication for future generation. Traditional electricity accepted as a premise that the load, and loads, on the system were independent and autonomous, and that the system had to provide generation to match this independent load. The premise was tenable under a monopoly franchise with captive customers, especially when the requisite generation came in large discrete lumps readily amenable to central planning. In a liberalized context and with today's technology options, however, the premise that generation has to expand to match independent load is a misconception and potentially a dangerous delusion. Governments and their agencies continue to present scenarios and analyses purporting to demonstrate the 'need' for new generation, to meet postulated increases of load. However, short of renationalizing electricity systems, the scenarists and analysts have no direct way to implement proposed plans for - say - new nuclear power stations, or any other form of generation. The owners and operators of other generators on a liberalized system would be outraged if government itself undertook to construct new generation that would compete with existing generation privately owned. Indeed private generators are already up in arms about indirect government support and preferential treatment, including tax breaks, grants and other financial assistance, given to one generator or one form of generation and not to others. Controversy rages, about comparative 'subsidies' to fossil-fired, nuclear and renewable generation in various places.

A more fundamental question, however, needs to be asked: why should generation per se qualify for government support that is not made available to loads? Why does electricity policy continue to assume that loads are autonomous, but that generation is not? Historically, generators were much larger and much less numerous than loads, and either directly or closely overseen by government. For straightforward practical reasons generation was therefore much more readily amenable to government policy intervention. As systems evolve, and generation becomes smaller, more numerous, more variously owned and more decentralized - in fact increasingly similar to loads - the asymmetry of policy focused primarily on generation is going to become egregious.

Many governments have recently expressed strong opinions about the future of electricity, seeking policy measures to achieve 'security of supply', affordable electricity services, and environmental and social sustainability. Henceforth, however, governments must recognize that electricity policy will have to rely on less direct methods to influence the evolution of electricity systems. Instead of explicit central planning and implementation of system expansion and change, governments will have to establish a fundamental framework within which front-line electricity decision-makers - generators, network planners and operators, and electricity users - must operate. Such a framework, already well within the accepted powers of democratically-elected governments, will have to evolve significantly from that which is now tacitly in effect in even the most liberalized electricity regimes; and it will have to embrace not just generation and networks but complete systems, including loads.

Governments may decide, for instance, to impose minimum technical and physical standards, and indeed a straightforward ban on electric technologies, including end-use technologies, with inadequate performance. They may widen so-called 'energy taxation' beyond fuels and electricity to embrace also, and more particularly, taxes on energy assets - not only power stations and networks but also buildings and appliances. Governments may also have recourse to many other financial measures, such as grants and early depreciation, as well as procurement and regulation. They should revisit and revise existing subsidy regimes for electricity assets and electricity fuels, to foster developments they desire and discourage the undesirable. Over time, such policies and policy instruments should widen to embrace symmetrically the entire interconnected system, including in a balanced way both the generators and the loads that may or may not be connected to the system at any given instant.

One obvious consideration will be a shift away from policies preoccupied with short-term commodity transactions in flows of electricity priced by the unit. Instead, policies will have to encompass whole circuits and systems - not only generation but also networks and loads - treated as coherent arrays of assets functioning together to deliver services. Appropriate business transactions will then, for instance, include the payment of fixed fees in exchange for having the use of available assets as and when they are desired, with no reference to measured or metered flows of electricity through the assets that deliver the services. So-called 'capacity payments' for keeping generating capacity available when not immediately required are a particular example of this approach. In suitable circumstances the approach can be generalized, so that customers pay fixed fees for services they then use as and when they wish..

Needless to say, where traditional and what might be called 'post-traditional' or 'transitional' electricity systems already exist, any such radical change is going to be both piecemeal and gradual. Around the world, electrical loads in thousands of gigawatts expect to have electricity available as before, without interruption or dislocation. In many instances significant interruption could threaten lives. The very continuity of electricity use makes any change in system characteristics, especially technical characteristics, demanding and difficult even when the whole system except the loads belongs to a single owner and operates as a monopoly. For a post-traditional, transitional system the difficulty of changing technical characteristics while maintaining the system in continuous stable operation is multiplied.

For those in charge, the simplest answer is not to change; and many owners of traditional generation are likewise determined to keep things more or less as they have been hitherto. Hence the running battles now raging in many places about connection and operation protocols for small-scale decentralized generation and cogeneration, local and on-site. Until recently such local and on-site generation has largely relied on diesel engines, raising issues of pollution and noise as additional obstacles. Gas engines are more acceptable; so are microturbines, Stirling engines and fuel cells, all of which are now or soon will be commercially attractive. But such local generation still faces stubborn opposition in some quarters, as Working Paper 3 will discuss. Although couched in technical terms, the battles are actually about comparative financial advantage in a competitive context. That does not make resolving them any easier. The possibility, indeed, exists that the most rapid and sweeping change in how we think about and organize electricity may happen where no 'legacy' assets or institutions impede the change - in the parts of the world where two billion people are still waiting for electricity and the services it makes possible. Unfortunately, however, all too often the authorities in these countries have an even more traditional view of electricity than that of their OECD counterparts, and are a tempting market for outdated technology. For this and other reasons, the technical issues arising from changing electricity arrangements essentially anywhere in the world are dwarfed by the political issues.

The politics of changing electricity start with a straightforward key question: who now decides? Who decides what new system facilities to build, when and where - and why? Who decides which facilities to operate, and when? In traditional electricity, the owner-operators of generating plant and networks decided on how to operate and how to expand the system, under the direct or indirect oversight of the relevant government or government-appointed regulator. The planners forecast the future growth of electricity use on the system, and added additional facilities, generating plants and networks accordingly, to meet the increased use anticipated. In selecting technologies they used techniques of comparative investment analysis that routinely failed to anticipate costs accurately, or even approximately. Politically, this often caused some embarrassment; but central planners were much more concerned to avoid the political fallout of blackouts or power cuts. Surplus and redundant generation and network capacity was insurance against such political fallout; and it was paid for by captive customers.

In the post-traditional transitional context, however, both the decision-makers and the criteria they apply have changed fundamentally. The decision-makers are likely to be private companies, often multinational, with wide-ranging holdings of assets, often in several different countries and on several different electricity systems, not necessarily interconnected. Neither the management nor the staff have any particular dedication to keeping the lights on. Their overriding interest is the entirely respectable objective of returning a profit to their owners and shareholders. The criteria they apply to investing in and operating electricity assets are those they think appropriate to fulfil this objective. In the case of generation, in the first decade or so of liberalized electricity, the choices they have made have been at best only intermittently successful. At liberalization they inherited many existing plants based on traditional technologies and fuels, especially coal-fired and nuclear steam-cycle plants. For investing in new plants, however, they have largely abandoned this tradition, opting instead for gas turbines burning natural gas, usually in combined-cycle stations.

If liberalization did not precisely bring about this change of generating technology, it certainly encouraged it. A gas-turbine generator can be efficient and economic at a much smaller size. It can be ordered, installed and in operation in under two years. Firing natural gas it requires no fuel storage; it produces no solid waste, and its emissions can be very low. It can therefore be sited much more easily, close to users and indeed on the site where the electricity is to be used. It also lends itself well to cogeneration, producing both electricity and usable heat, with overall fuel efficiency above 80 per cent.

In the early 1990s, in the first rush of enthusiasm for liberalization, new gas turbine stations tended to be aggregations of generators on a single remote site, essentially equivalent to traditional steam-turbine and water-turbine stations in the traditional system configuration. Gradually, however, understanding dawned that gas-turbine technology makes smaller stations closer to users not only feasible but frequently desirable, reducing the need for long transmission lines and the accompanying losses, especially when generators can be located actually on site. The trend toward more and smaller generators closer to users is a sharp break with the traditional trend toward ever-larger stations ever farther away. Indeed owners have since shut down many of the inherited traditional plants, sometimes modern, fully functional and not yet amortized.

In the early years of liberalization, privatized operators with extensive portfolios of inherited generation, notably in the UK, operated their units, not just plants but individual turboalternators, in ways that maximized the overall return to the company. Instead of running all available generators all the time, they withheld some from the 'pool' of generation. The effect was to reproduce within the generating company a subset of the traditional 'merit order', when all generation on the system belonged to the same owner and individual generators were called on in order of operating cost, the cheapest first. Withholding generators from the 'pool' reduced the margin of surplus capacity on the system, and therefore raised the wholesale price of electricity. As a result the generators actually operating earned more revenue for the company per unit of electricity output.

At the time the procedure was entirely legal; but the liberalizers, making up the market rules as they went along, nevertheless decried the companies for 'gaming the system'. Partly because of consequent changes in regulation and market rules, and partly because the original privatized companies have themselves undergone so many changes, owners of generation, even large multinationals, now tend to concentrate on individual plants as profit centres. The usual system constraints, however, still apply. Any given unit can operate only according to the overall requirements of the system, however determined, despatched either by traditional merit order or on the basis of some market. Many generating units operate, of necessity, only part of the time, sometimes such a brief part that the unit does not even earn its cost of capital.

This was always true for a traditional system, with costs and returns aggregated and averaged across the portfolio. On a liberalized system, however, it is already causing trouble. Each individual generator is paid according to how many units of electricity it delivers into the system. The owner therefore wants it to operate at full output all the time, to earn as much revenue as possible. Generators already in existence and in operation on a system do of course follow load and respond to peak loads, mainly because for many such generators this is the only way the system allows them to operate at all. No one, however, wants to invest in a new generator to follow load, much less to operate only at times of system peak load; market prices for electricity are too unpredictable and the investment therefore too risky.

A traditional system has a portfolio of generation in which each unit has a role to play in meeting the overall load at any given time, with technology and fuel appropriate to that role. Since liberalization, however, the traditional portfolio has given way to a default situation in which the essential function of load-following at any given moment devolves onto whichever plants and units happen to be left after all the rest are operating continuously - whether or not these leftover units are technically suitable for the function. So long as the system continues to include a 'tail' of such plants and units, whose owners are willing to keep them available for intermittent operation, system stability can probably be maintained. But owners are already withdrawing from markets, writing down the value of generating assets they consider underused, mothballing or even retiring them. Under such conditions a system can go from an apparent glut of generating capacity to a shortage with dramatic speed.

Electricity users in general want reliable services and lower bills, as Working Paper 4 will discuss. However, the aim of the liberalizers and the competitive market in units of electricity, acclaimed triumphantly over and over, is ever-lower prices per unit of electricity. This is not the same as lower bills; indeed recent research suggests that a higher unit price, encouraging more efficient use, may actually lead to a lower bill for the same service. In any case, sooner or later, unless the obsessive aim for a lower unit electricity price is modified, it may become incompatible with maintaining adequate reserve generating capacity even to meet peak load, to say nothing of fault conditions. One way to modify the market, for instance, would be to pay owners directly for keeping generators available for use, even when not used - a so-called 'capacity payment', as mentioned earlier. Market purists decry any such measure, as diluting the market forces that are supposed to drive the participants and determine their policies and their decisions. But a pure market in ephemeral units of electricity may not indefinitely be capable of keeping the lights on.

How generators should be paid is not the only financial question-mark hanging over the future of generation on liberalized electricity systems. The costs of generation are at last, belatedly, coming under the kind of scrutiny they should have received long since, both before and after liberalization. As noted earlier, the analyses of costs, particularly investment costs, for traditional generation on traditional monopoly systems was demonstrably unsatisfactory for decades, to put the matter no more strongly. Since the costs in question were paid by captive customers with no recourse, cost-analysis remained more a matter of wishful thinking and public relations than a serious discipline. Planners decided what generation they wanted to build, when and where, and produced cost estimates to support the decision; but the cost estimates often looked both post hoc and arbitrary.

Liberalization exposed the shallowness of such estimating techiques, by inflicting their consequences not on captive customers but on shareholders and bankers. Even for existing generation, the purchasers of power stations being privatized found themselves not so much in a market as in a lottery, in which they might earn a substantial return on the investment, or might instead be forced to write off hundreds of millions of dollars or pounds on a plant unable to pay its way at all. Investment in new generation proved to be yet riskier. In the UK, for instance, after liberalization, entrepreneurs invested in an assortment of new combined-cycle gas-turbine (CCGT) stations, burning natural gas purchased on long-term contracts at what then appeared to be a bargain price. These stations forthwith undercut most of the existing traditional steam-cycle stations on the system, including several very large modern stations, forcing them out of business. Within five years, however, a subsequent wave of CCGT stations came into operation, using yet newer gas turbines, more efficient and cheaper, burning natural gas at an even lower price. The first wave of CCGT stations, still less than five years old and far from fully amortized, in turn found themselves being crowded off the system by generation cheaper still. For those whose objective was a lower unit price of electricity this was evidence of the success of liberalization. For many electricity entrepreneurs and investors, losing their shirts, it was evidence that electricity was now a business they did not want to be in.

In an interconnected electricity system, not only the revenues but also the costs of a particular generator depend to a significant extent on the rest of the system and how it operates. To give but one obvious example: if the system load and other generation make a given steam-cycle unit operate at below maximum capacity - as is often the case - the unit's fuel-efficiency falls, and its output therefore costs more per unit. Against this background of continually shifting non-linearity, the common practice of stating the 'cost' of a unit of electricity as '2.7 cents per kWh' or some similar figure is frankly indefensible. It becomes yet more so when such numbers, stated even to three significant figures, are used to advocate or justify choosing to invest in a particular generator technology or design as against others claimed to produce 'more expensive' electricity. The practice was disreputable even when the choice lay between otherwise similar technologies, as for example between types of coal-fired or nuclear generation. When the choice is between technologies so fundamentally different, say, as gas-fired combined cycles and photovoltaics, the use of such purported cost comparisons becomes egregiously tendentious.

In any case, moreover, recent studies suggest that traditional techniques of estimating the anticipated cost of electricity from a proposed generator may be inherently and seriously flawed. In 2002 Shimon Awerbuch, at the time a senior advisor in the Renewable Energy Unit of the International Energy Agency, produced a draft report called *Estimating Electricity Costs and Prices: The Effects of Market Risk and Taxes*. The report demonstrated just how untrustworthy such estimates can be. The thesis was straightforward, if complex to demonstrate. It declared that the traditional approach to estimating the cost of electricity from a particular generator is based on engineering economics rather than financial economics. Engineering economics fails to apply a premium to account for the risk that over the life of the generator fuel prices and fuel taxes may vary from those used to estimate the cost of electricity. So long as alternative generating options have broadly similar risks, and those risks move in the same direction with contingencies, the effect on choice of generating technology may be modest to trivial. However, between technologies with dramatically different risk profiles, failure to account for risk may drastically skew the comparison of costs.

Consider, for instance, comparing fuel-based generation with non-biomass renewable generation - say, a gas-fired combined cycle station with a wind farm. An investor trying to choose between putting money into one or the other will be aware that the price of natural gas may rise unpredictably during the operating life of the combined-cycle station. The investor will therefore require a higher return, to compensate for the risk that the station output may not be as profitable as anticipated. That in turn will increase the cost of generating a unit of electricity. For the wind farm, however, no such fuel-price risk arises. Apart from small and predictable running costs for maintenance, the entire cost of the wind farm is the initial capital investment, known at the outset and unvarying over the operating life of the wind farm. Using well-established techniques of financial analysis demonstrates that adding renewable generation free of fuel-price risk to a generating portfolio otherwise based on fossil fuels reduces the risk for an equivalent return, or alternatively increases the return for the same risk.

Again, an increase in fossil fuel prices appears to be strongly correlated with a downturn in overall economic activity, reducing demand for electricity and aggravating the problem of higher electricity cost. Renewables, however, whose costs are mainly servicing capital charges, may actually benefit from the economic downturn, if interest rates fall. Adding renewables thus diversifies the portfolio and reinforces its robustness against unwelcome surprises. The prevailing assumption is that official support for renewables, especially in Europe, is making electricity more expensive. The financial reality, however, may well be that adding renewables free of fuel-price risk should reduce the overall investment cost of generation on systems. Developing and extending this ground-breaking comparative analysis of generating options, refining and sharpening estimates of comparative cost in this way could have striking consequences for the technology choices that drive the evolution of electricity systems.

Other aspects of comparative generating cost are likewise controversial. For instance, environmental impacts associated with different forms of generation have been called 'externalities' because their putative costs are borne not by the generator but by the environment within which it operates - the air, the land, the water, and by extension the other people who use the same environment. The decision as to whether and how to account for such externalities has a dramatic effect on the cost, operability and profitability of individual generating plant. Over the years analysts, planners, legislators and regulators have tried to quantify these externalities, and incorporate some suitable numerical and financial measure into the costs attributed to generators. The judgments are necessarily arbitrary; some consider them invidious. Comparative quantification, perhaps in cents or pence per unit, of the different environmental impacts of, say, coal-fired, nuclear or wind-powered generation is ultimately political, not scientific. The most successful approach thus far has been so-called 'cap and trade', as applied to sulphur emissions from fossil-fired plants in the US. But the crucial step is the political one of imposing an upper limit on total permitted emissions, and allocating permits accordingly; only thereafter does the market in permits come into play. The political arm-twisting involved is yet more apparent in the so-called 'grandfathering' of the oldest and dirtiest coal-fired plants in the US. Allowing them to operate as before makes them accordingly much the cheapest generators to run, because they do not have to pay for their externalities. This in turn keeps cleaner and more environmentally acceptable plants off the system.

All in all, what with assorted, perverse and often enormous subsidies to fossil fuels and nuclear power, and more modest but more visible subsidies for renewables; with inadequate accounting for risks; and with arbitrary and distorted provisions for externalities, only one conclusion can be drawn. As far as comparative costs are concerned, the choice of generation is political, not economic. Electricity costs stated as so many cents or pence per kilowatt-hour are just window-dressing after the fact, an artefact of prior decisions otherwise concealed. The same applies to the other original nineteenth-century criteria for choice of generation. Size and location are profoundly affected by politics, especially planning constraints on siting and operation. So is connection to networks, as Working Paper 3 will discuss. Once we acknowledge that the choice of generating technology, including its type, size, location and network connection, is fundamentally political, electricity policy takes on a significantly different flavour.

In particular the role of government appears in a new and disconcerting light. The headline purpose of liberalization was supposed to be to remove government from the business of making, selling and using electricity. That was always an exaggeration, to put it mildly. Regulation was and is construed as keeping government at arm's length; but this is only plausible when nothing too untoward happens. If the lights go out, however, the government is in the front line, no matter who else may be nominally responsible - as governments in California, Auckland, Sao Paulo, Ontario, the northeastern US and elsewhere have discovered with discomfort.

Since the 'oil shock' of 1973-74 governments have espoused what they call 'energy security' as a primary objective of energy policy. They have yet, however to realize in practice just how different the 'security' issue is for electricity policy in particular. In this context, 'energy security' or 'security of supply' is usually construed to mean a secure supply of affordable fuel for electricity generation, especially oil and more recently also natural gas. For fuel-based electricity, governments in most OECD countries appear to believe that the main problem for 'security of supply' is now with imports of natural gas, potentially over long distances and from regions politically unstable. That is undoubtedly an issue, and important; but most attempts to address it nevertheless miss the much more immediate vulnerabilities closer to home.

As regards electricity, what matters is the security of supply of the services delivered by electricity. What matters is that the lights stay on. Interruption of fuel supply for fuel-based electricity does indeed pose a potential threat. But electricity is a process. Any interruption of the process, at any point in the system, may make the lights go out; and the process can be interrupted much more immediately and abruptly than by loss of fuel supply. Some such interruptions are local and can be readily rectified - a blown fuse, a burnt-out incandescent lamp. Others, however, may affect the entire system, in minutes or even seconds, blacking out a whole country. A storm bringing down a transmission line can cause a cascade collapse over a vast area, and leave it without electricity for days. In recent years such major blackouts have struck Brazil, Canada, India, France, Sweden and the US, among others, costing untold sums. Moreover, such a catastrophe may be triggered not only by an act of nature but also by an act of human malevolence. This possibility is already exercising governments at senior levels.

The part of the system most vulnerable to disruption is not, however, generation, but the network, including cables, towers, and substations, as Working Paper 3 will discuss in more detail. Nevertheless, generation is the key to reducing the vulnerability of the network. The most effective measure is not to reinforce the network but to reduce its importance - in particular, to locate generators closer to loads, minimizing the amount of circuitry needed to complete the electricity process. If security of supply of electricity services is giving rise to serious concern, the clear implication is that small-scale generation close to loads is a form of insurance that may be worth a premium, at least to users with sensitive loads. This will be yet more so for local infrastructure generation such as photovoltaics that requires no fuel and is not therefore exposed to the threat of disruption of fuel supply.

To the extent that governments consider themselves responsible for keeping the lights on, policies to encourage on-site infrastructure generation should therefore be a central part of any package intended to enhance the security of supply of electricity services. Any government recognizing that real energy policy is much wider than traditional fuel and power policy, and that traditional methods of comparative costing of generation are grossly inadequate, has ready access to appropriate policy levers - notably differential taxation of energy infrastructure assets, including buildings. To implement such policy, however, a government must have the courage to challenge the stultifying inertia of tradition - traditional concepts, traditional institutions and traditional mindsets.

Where will this happen, and when? Some look to the vast areas of rural developing countries such as China, India and much of Africa, in urgent need of electricity services and unencumbered by legacy assets and legacy traditions. The opportunity to leapfrog directly to innovative electricity systems and institutions is there for the taking. Unhappily, however, in precisely those parts of the world most in need of innovation, electricity policy tends to be in the grip of tradition more hidebound even than that in OECD countries.

The implication is unmistakable. If the world is to gain the benefits of innovative electricity, starting with innovative generation, OECD countries will have to show the way. Moreover, even in the most liberalized frameworks, OECD governments cannot sit back and pretend that electricity policy is now out of their hands - that private enterprise is henceforth responsible. The public does not believe it, because it is not true. For generating change, and for keeping the lights on, governments must forthwith take the lead. The time to do so is now.