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Networking Change

Working Paper 3

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As electricity systems worldwide battle through turbulent change, one key question emerges: what is the network for? Unfortunately, policymakers rarely ask this question, much less answer it. That may be because they think they already know the answer, and see no reason to doubt it. It may, however, be because the question simply does not occur to them. It should. As electricity evolves, a central theme must be the evolving role of the network. Now and henceforth we need to ask and keep asking, explicitly, what the network is for. More precisely: we need to know what different parts of the network are for; who is involved; why; and how. The answers are changing as networks are changing. This evolution is going to go much farther than most of us yet realize, and perhaps much faster. (See also the author's *Network Futures*, Working Paper No. 4 for Transforming Electricity (1997); *Transforming Electricity* (RIIA/Earthscan 1999); and *The Electric Challenge* and *Generating Change*, Working Papers Nos. 1 and 2 for *Keeping The Lights On* (both 2003).)

The traditional network is important as a starting point, not only because it still broadly prevails, but also because it continues to shape the thinking of planners and policymakers, even where traditional networks do not yet exist. Consider, then, how electricity networks came to arise. At its simplest, electricity does not need a network. In an electric torch a single loop of wire connects the battery to the bulb - an electric circuit, closed and opened by a switch. This single circuit is an inherent feature of the process by which you produce electric light. It is either working or not working - on or off. However, as soon as you want to connect more than one load to a generator, or more than one generator to a load, the circuits multiply and interconnect: you have the beginning of a network. In the early days of electricity, before the 1880s, arc-lighting systems might have a number of lamps running from a single generator. But the whole system - generator, wires, switches and lamps - all belonged to the same owner-operator, who paid the investment and running cost and used the entire system as desired. The network involved was an integral part of the system, as essential as the crankshaft in a steam engine. Just as the output of a steam engine was motive power, so the output of an arc-light system was illumination. Moreover, just as someone owned and operated the complete steam engine - not merely the crankshaft or the flywheel - so someone owned and operated the complete arc-light system. That owner-operator bore the whole responsibility for keeping those particular lights on.

At the beginning of the 1880s, however, this straightforward arrangement began to change. Thomas Edison, like several other contemporary entrepreneurs in North America and Europe, understood that only by pursuing economies of scale could he hope to make electric light competitive with gas light. With the generating technology then available, that meant using a larger steam engine and dynamo; but such a large generator would produce more electricity and therefore more electric light than a single client could then expect to use on one site. The obvious solution was to enroll multiple clients on multiple sites, interconnecting them all to the same large generator. That in turn entailed laying a network of cables between sites and through public space, a practice that might have been controversial but had already been sanctioned for gas pipes, not to mention water and drains. At the outset, nonetheless, Edison retained title to all the constituent parts of the system. His company owned generator, network, switches and lamps, just as if the whole system had been on one site. Edison charged his clients according to how many lamps they used; he was selling electric light.

In the mid-1880s, the invention of a practical electricity meter abruptly altered this arrangement. Once the meter intervened, the system was no longer delivering electric light. It was delivering electricity, bought and paid for by the measured unit and used in lamps the client purchased and owned. Soon thereafter, even the wires and switches on a customer's site belonged to the customer, not to the owner of the rest of the system. The network itself was divided between different owners. To be sure, the owner of the wires on a client's site - the client - paid no attention to them. So long as the lights stayed on, the wires were simply part of the building. If the wires malfunctioned, however, the client had to find and pay an electrician to fix them. If a lamp burned out the client had to buy and fit a replacement. Even as late as the 1920s some systems would replace lamps, just to keep customers using electricity; but in general as long as electricity reached the meter, the rest of the system bore no responsibility for keeping on the lights of any particular client. Within the 1890s the same became true of electric motors and thereafter of other electrical appliances on clients' premises. The responsibility of the owner-operator of the system stopped at an intermediate point on the network - the client's meter. The client became a customer for electricity, bought and paid for as a commodity with an established price per measured unit. The network acted as a delivery conduit, carrying electricity from the generator to the customer's meter, and dividing up the large output of the generator into quantities appropriately small for the aggregate load on the customer's side of the meter.

The electricity network became closely analogous to its precursor, the town-gas network - with one important difference. Town gas was a commodity, a physical substance flowing through the network of pipes. It could be stored; the gas could be produced as desired and used as desired, with no necessary connection between production and use. Electricity, however, was not a physical substance, but a process, occurring instantaneously throughout the network of wires. Electricity, as a process, could not be stored; it had to be produced more or less exactly in the quantity and at the time that it was being used, continuously. This difference was to have a fundamental effect on the shape and operation of electricity systems - an effect now overdue for reassessment.

Other substantial changes quickly ensued. Edison and fellow entrepreneurs assumed at the outset that the central-station systems being set up would generate and deliver so-called 'direct current' or DC, always flowing in one direction like that from a battery - another attribute paralleling the behaviour of the town-gas network. By 1890, however, George Westinghouse and Nicola Tesla had shown that alternating current, AC, surging rapidly back and forth in the wires, had several marked advantages over DC. It could be generated with ease by a rotating machine; it could power an elegant motor; it could be carried with a more economical arrangement of conducting cables; and - perhaps most important of all - it could be used with a transformer, to increase or decrease the voltage, and inversely the current, easily and efficiently.

This offered a solution to a major problem of DC. Electric current in a wire heats the wire, wasting energy; and doubling the current quadruples the heating effect. The longer the wire the worse the losses. Central-station systems like those of Edison, based on DC, were severely hampered by energy loss from the network; the more widespread the system the worse the losses, making system expansion prohibitively costly. To reduce the energy loss you must either use heavier more expensive wire or a smaller current. For a given flow of electrical energy in a given wire, doubling the voltage halves the current; so the higher the voltage the lower the current and the energy losses. Accordingly, by introducing a suitable transformer into an AC circuit you can raise the voltage high enough to reduce the current and the corresponding losses dramatically, making a much longer line feasible. At the other end of the circuit another transformer can bring the voltage back down to a level suitable for whatever loads may be included.

Unlike a DC network with electricity flowing in one direction, an AC network behaves very differently from a gas network. No gas analogue of AC electricity, surging rapidly back and forth, exists; AC is much more obviously a process than DC. An electric current always carries with it a magnetic field. If the current changes, so does the magnetic field, with profound effects on the combined 'electromagnetic' behaviour of the system. Designing and operating an AC system must take account of an array of continuous electromagnetic interactions far more complex than anything associated with DC. Indeed, a significant proportion of the energy associated with an AC system is required simply to maintain and manage the accompanying magnetic fields - so-called 'reactive power'. Yet with AC, unambiguously a process throughout an entire system, long-distance transport of electricity became feasible. Paradoxically, the AC process, by making remote large-scale generation practical, facilitated treating electricity as a quasi-commodity for nearly a century.

From the 1890s onwards, the rise of AC brought about a fundamental change in the configuration and operation of electricity networks. As AC systems expanded, each AC network came to have two distinct subsections, one operating at substantially higher voltage than the other, linked by banks of large transformers in so-called 'substations'. The section at higher voltage carried electricity comparatively long distances with limited losses - so-called 'transmission'. The section at lower voltage delivered electricity to customers' meters - so-called 'distribution'. Eventually, both transmission and distribution became further stratified, with more and more levels of voltage for different purposes, interlinked by transformers, but all operating in real time as part of one complex continuous process. In such a system all the rotating generators on the system spin at the same rate, in step with one another; the entire system is 'synchronized'. An interconnected synchronized AC system is effectively a single machine, operating continuously in real time. In due course one gigantic AC machine might come to cover an entire country, or even more.

Initially, on any given system, both the transmission and the distribution sections of the network belonged to the same owner-operator; the only other owners involved were those on the customers' side of meters. The system owner-operator had to plan, install, operate, maintain and pay for the whole network, except the wires of customers. In some places, for instance London, different owner-operators established competing networks, often along the same streets. Elsewhere, however, the first network to be established in an area received a head start sufficient to prompt potential competitors to seek more promising territory. In many places, for reasons of local politics, civil or municipal governments set up generators and networks. These authorities then used their political leverage, particularly over public space and waterways, to refuse permission to potential competitors to set up competing networks. This was the first manifestation of what subsequently became the almost universal practice, to grant an electricity network a political monopoly throughout a specified franchise area.

Promoters of the monopoly franchise, such as Samuel Insull of Commonwealth Edison in the US, argued that an electricity system with its network was a 'natural monopoly' - that permitting competing systems in the same locality would make electric light and motive power more expensive to users. The argument was controversial, and certainly self-serving. Whether or not the electricity network itself could then be considered a natural monopoly, other competing options included for instance on-site electricity generation, gas light and steam power. Nevertheless, natural or not, from the 1920s onwards electricity systems around the world - not just networks but whole systems - metamorphosed into political monopolies. In the franchise area no one else could generate electricity to sell; no one else was allowed to run an alternative network through public space. Electricity users became captive customers. The monopoly franchise system operator, in turn, had to deliver all the electricity that users wanted, where and when they wanted it, at a price determined by government or a government-appointed regulator. Sometimes different parts of the network belonged to different owner-operators; for example, a number of low-voltage local distribution systems, separately owned and operated, might all receive electricity from a single high-voltage transmission system. But each separate part of the network was still a franchised monopoly in its area; and the entire interconnected network was still synchronized.

In this form of electricity system, what might be called 'traditional electricity', the role of the network was clear and unambiguous. The network was the conduit that delivered remotely-generated electricity to users. To fulfil the commitments of the monopoly franchise, the network had to have enough carrying capacity in all circuits to accommodate the peak load, with a margin of redundancy to spare. It had to reach all generators and all users on the system; adding generators or users meant adding network capacity. The network entailed investment and running cost, but did not itself produce revenue; expanding the network could be justified only if the consequent overall effect on the system would be to reduce the cost of generation or increase the income from users. In the centralized synchronized AC process, the network aggregated generation at any instant, allowing the operator to favour the output from the cheapest generators and 'dispatch' them accordingly, holding more expensive generators in reserve for peak loads. The network also offered a way to replace faulty generation, almost instantaneously if necessary to match load, provided that spare generation was available and ready to produce.

For more than half a century, over much of the world, this arrangement worked remarkably well. Networks spread ever more widely, and became ever more interconnected, even across national borders. After the devastating disruption of the second world war, the expansion of electricity systems was unceasing; and all the systems were based on the same common technical model. Large power stations generated electricity as synchronized AC and delivered it to users over networks including high-voltage transmission and lower-voltage distribution. Pursuing economies of scale, system planners designed and built ever-larger stations, ever farther away from users, requiring ever-longer transmission networks at ever-higher voltages. The customers of monopoly franchise systems paid all the costs, but were generally unperturbed by their captive status, because until the early 1970s the cost of electric light, motive power and other electricity services steadily declined. The traditional technical configuration was so robust that it could function under many different institutional arrangements. Government owner-operators, private owner-operators, cooperatives, municipal, regional or national organizations, capitalist, communist or colonial regimes, all embraced the central-station synchronized AC form of electricity system - with admittedly varying degrees of success.

Even in OECD countries, the success of traditional electricity was not without controversy. Networks expanding into rural areas, financed by lavish subsidies from taxpayers, wiped out many local electricity systems based on wind or microhydro. Transmission towers on rural skylines attracted vehement objections even in the 1950s, when power stations themselves were still accepted without protest. However, objectors did not dispute the desirability and indeed necessity of transmission lines, as an inherent feature of the electricity system; they argued only to put a line somewhere else, 'not in my back yard', probably the earliest occurrence of NIMBY.

Perhaps the first serious setback to traditional electricity was the system collapse of November 1965 that blacked out most of the northeastern US and eastern Canada. By that time people in most parts of most OECD countries took traditional electricity pretty much for granted, assuming that someone somewhere was keeping the lights on. The big blackout was a dismaying jolt. It demonstrated what most people had long since forgotten, that electricity is a process - that a traditional electricity system is a single gigantic machine operating in real time, and that it can also shut down in real time, over thousands of kilometers, in minutes if not seconds. The blackout prompted much breast-beating by electricity companies, who forthwith set up the North American Electric Reliability Council, NERC, charged to prevent any recurrence of such a problem. The members of NERC all held franchised monopolies. The measures they proposed, including enhanced redundancy on interconnected networks, given the go-ahead by regulators, were in due course financed by their captive customers, as a form of compulsory insurance. Other OECD countries, whose electricity users could mostly afford the cost, took similar measures. Wherever possible, systems opted for multiple redundancy, both generation and networks, to address the problems of reliability. But the status of traditional electricity as a process occurring throughout a single machine meant that the possibility of shutdown remained inherent in the technical configuration of the system. In subsequent years, one system collapse after another, all over the world, underlined this inevitability.

The year 1965, indeed, could be said to be a watershed for traditional electricity, the height of its success and the beginning of its decline. The mid-1960s saw the advent of rapidly expanding programmes of investment in nuclear generation, and also in other very large steam-cycle stations, many of which in due course experienced severe delays and cost overruns, some even cancelled when nearly complete. Nuclear stations provoked mounting opposition in many countries. Major hydroelectric dams in developing countries caused bitter controversy. Gaseous emissions, notably sulphur and nitrogen oxides, and other forms of pollution made fossil-fueled electricity generation a key target of environmental concern, prompting legislation and controls. People still expected the lights to stay on; but electricity organizations, from having been unquestioned benefactors, gradually fell into public disfavour. Networks, especially the visual impact of transmission lines, still excited popular hostility; but from the 1970s onwards power stations themselves became the chief offenders.

In 1978 the US government under Jimmy Carter enacted ground-breaking energy legislation, including the Public Utilities Regulatory Policy Act (PURPA). By fostering the concept of 'non-utility generators' permitted to sell electricity into existing systems, PURPA challenged the long-standing assumption that an electricity system had to be an integrated franchised monopoly. Practical implementation of PURPA was hotly controversial. According to PURPA, a 'non-utility generator', perhaps a wind farm or a cogenerator, was to be paid the 'avoided cost' that the system would otherwise incur; but computation of this putative 'avoided cost' provoked bitter disputes and recriminations. PURPA nevertheless opened a whole new direction for the technical, financial and institutional evolution of electricity. Policymakers around the world followed its ramifications intently.

For a variety of reasons, therefore, by the late 1980s traditional electricity organizations were vulnerable to the sudden challenge presented by free-market advocates propounding a new vision for electricity. Electricity, they declared, should no longer be a 'utility', provided by a franchised monopoly either a part of government or regulated by government. Electricity should be a commodity like any other, bought and sold in a competitive market just like oil or coal - or perhaps more like natural gas, because electricity, like natural gas, required a permanent network of conduits to deliver it. The free-market concept of electricity, launched in Chile under Augusto Pinochet, was embraced enthusiastically by the UK government of Margaret Thatcher. In less than two years, from 1988 to 1990, the concept evolved frenetically from purely theoretical to practical reality. Within another year or two British electricity evangelists and fellow believers had spread the new gospel of 'privatization' and 'restructuring', or 'liberalization', across the world. But its hectic inception left fundamental questions not only unanswered but unasked, particularly about the role and function of the network in liberalized electricity.

For nearly a century an electricity network anywhere in the world had fulfilled a concise and well-understood set of functions. Its primary role was simply to deliver electricity from generators to users, as a conduit analogous to a gas pipeline. Since almost all generators were orders of magnitude larger than almost all loads, the network divided the large output of individual generators into quantities small enough for individual loads. The network also allowed a central controller to select the cheapest generators to serve the total load on the system at any instant, and to replace a faulty generator with a backup generator, almost immediately if necessary to keep the lights on. The owner-operator decided how to maintain, modify or expand the network to fulfil these functions; and the captive customers of the monopoly paid whatever charges the government or regulator authorized. The arrangement was cogent and coherent, and at least in OECD countries it worked - not flawlessly but well enough to keep most lights on almost all the time. Where it worked less well, in communist or developing countries, the reasons were usually obvious, and political and financial rather than technical.

Electricity liberalization, however, involved a fundamental change in the status and function of the network. The guiding concept of liberalization was the creation of a 'market' in electricity. In principle, each generator would bid to sell its output, and each user would bid to buy the electricity required. Each transaction would entail agreeing to deliver and accept an appropriate amount of electricity over a stated period of time, at an agreed price per unit. The aggregate of all the electricity transactions in progress at a given moment would determine the amount of electricity flowing through each part of the network at that moment. In effect, the network itself would become a sort of 'marketplace' in which buyers and sellers would meet to do business. The more multifarious the network interconnections, the more liquid and effective the market. What mattered was not the actual execution of transactions but the very possibility of transactions.

To liberalize electricity systems, governments passed arrays of legislation establishing new frameworks for companies, markets and business relations. The accompanying rhetoric often referred to 'freeing the market' and removing government from the picture. According to the rhetoric, government would empower a regulator to launch the undertaking and guide it through its formative stages; the regulator would then recede gradually into the background, letting the market, in its wisdom, demonstrate the most efficient and economic way to keep the lights on.

It did not work out quite like that. The dilemma for free-market theoreticians was that generators and users might participate in a competitive market, but could do so only by means of a physical network that linked all participants, allowing them to share in the electricity process. This network, far from being competitive, was still a monopoly, if anything stricter than before liberalization. Every market participant, whether buyer or seller, had to comply not only with technical protocols for access to and use of the monopoly network, but also with a whole new stratum of financial and institutional rules that the regulator propounded and enforced. These rules proved to evolve with dismaying speed, in ways that too often appeared incoherent and arbitrary. Instead of receding into the background, regulators expanded inexorably, impinging on every transaction and becoming key players with their own agenda, in what looked less like a free market and more like a free-for-all. In the UK, for instance, the regulator, after various vicissitudes, eventually became known as the Office of Gas and Electricity Markets, OFGEM. However, since its key responsibility was and is oversight of the monopoly networks, OFGEM might more accurately stand for Office of Gas and Electricity Monopolies. Similar considerations apply to regulators wherever electricity is being liberalized.

The theoretical neatness of the free-market idea collides with the reality of electricity as a process, in the existing traditional central-station synchronized AC system. In a complex multiply-interconnected network, electric currents flow according to the laws of physics, not those of commerce. Keeping the system stable demands not only that total electricity generated must match total load as it varies, instantaneously and continuously, but also that other aspects of the process stay within acceptable bounds - a whole catalogue of so-called 'ancillary services'. For instance, the reactive power that maintains the accompanying magnetic fields in and around the network does not register on a conventional electricity meter; but without it the AC system cannot operate. Some versions of electricity market assumed that generators would provide reactive power as before, without additional payment; market designers made no provision for any suitable transaction. Other market designers found themselves having to provide for such essential ancillary services under duress, impromptu, ad hoc and expensive.

Those who liberalized electricity appeared to be proceeding on the premise that - despite the consequent sweeping institutional and operational changes - networks would continue to function more or less as before. But traditional networks were already under significant stress, which liberalization tended to aggravate. Apart from the remote but non-trivial possibility of system collapse inherent in traditional synchronized AC, reliability and power quality were already coming up the agenda as issues. Networks, once part of the solution, were becoming part of the problem. In OECD countries and indeed elsewhere an increasing proportion of loads are now said to be 'sensitive', requiring not only an uninterrupted flow of electricity but very stable voltage and frequency. These loads, such as paper mills and similar continuous process plant, chip-manufacture, data-processing centres and server farms, also tend to be involved in activities with high added value, in which even brief outages or disturbances can be alarmingly expensive. A one-hour outage at a credit-card centre can incur costs in seven figures; a one-second outage on a chip line may ruin a multi-million dollar batch of chips. The desired standard is sometimes expressed as 'six nines' - that is, 99.9999 per cent reliability. Such a standard, however, is beyond the capability of a traditional synchronized AC network.

Networks that used to smooth out and reduce disturbances are now more likely to be the source of disturbances; and a synchronized AC system can propagate a disturbance a long way very fast.

Nor are sensitive loads the only problem for networks. At the beginning of the 1990s, liberalization coincided with the emergence of gas turbine generation for baseload operation. As earlier Working Papers have noted, this marked a substantial break with tradition, in which a better power station was always a bigger power station farther away. A gas-turbine generator firing natural gas can be economic at a much smaller scale, as well as cleaner and more environmentally acceptable; it can therefore be sited much closer to loads. That immediately has intriguing implications for networks. Other innovative generation adds further complications. Technologies already available or soon to be include wind farms, onshore and offshore; small cogeneration, using gas engines, Stirling engines, microturbines and fuel cells, even down to domestic scale; local wind generation, not only rural but also urban; local microhydro; and photovoltaics in many different applications. All these options require suitable network connections, operating protocols and other arrangements, often far-removed from traditional. As yet, provision of such network arrangements for innovative generation tends to be grudging, ad hoc and unpredictable. Network operators and regulators tend to cling to traditional mindsets about networks, regarding small-scale generation as at best uninteresting and not infrequently an active nuisance. But the pressure from innovative generators is steadily mounting; and efforts to develop appropriate protocols, regulation and legislation are under way in a number of countries. One consequence is already certain. As new generators and new users bring new attributes to electricity systems, the configuration and operation of networks is going to change. Networks that once simply delivered electrons may now have to make money, deliver transactions or deliver services, or perhaps all three. Networks may even foster - not hinder - change. But the transition will be neither smooth nor easy.

Network technology itself has lately seen major innovation emerge, albeit thus far more in theory than in practice. Even as liberalization came into the picture, substantial new breakthroughs were offering welcome additional capabilities to traditional synchronized AC networks. A suite of technologies called Flexible AC Transmission System or FACTS will allow network operators much more subtle control over flows of electricity through the many different circuits of a high-voltage network. Power electronics, able to switch and modify electric currents more than a million times those in conventional electronics, gives network designers and operators impressive leverage over system behaviour. Even Edison's favourite, direct current, has reappeared as a strikingly attractive addition to network portfolios, in the form of high-voltage DC or HVDC, able to double or triple the carrying capacity of high-voltage cables, requiring no synchronization of interconnections and able to block the passage of disruptive transients. In the US, for instance, the Electric Power Research Institute EPRI has developed a detailed 'road map' describing the successive introduction of innovative technologies, particularly network technologies such as these, into electricity systems.

However, even as these technologies are becoming commercial, they have collided with an unfortunate corollary of liberalization. On many systems where FACTS technologies, for instance, would benefit operators and users - notably in the US - the necessary investment has not yet happened, because no one is quite sure who will pay for it, or how. Transmission operators lack incentives. Under prevailing US regulatory arrangements, for instance, even if operators are earning a fair rate of return, they have little incentive to invest in enhancements that are efficient but relatively low-cost. Investing in towers and lines solves the problems more capital-intensively and hence creates better earnings. In the UK, by contrast, the regulator, now OFGEM, has allowed network operators, both transmission and distribution, to invest substantial sums for maintenance and upgrades. The guiding presumptions, however, remain that the networks still function according to performance criteria laid down in 1977 under the monopoly Central Electricity Generating Board; that they are still a delivery conduit for electricity from remote large-scale generators; and that investment is directed essentially to this end.

In recent years, to be sure, a succession of committees and other study panels have examined the status and prospects for what is still often called 'embedded generation'. The adjective 'embedded' is ambiguous, but usually refers to generation connected to lower-voltage distribution sections of the network rather than to the traditional high-voltage transmission section. But 'embedded' also carries the unmistakable connotation of generation where it is not expected or indeed supposed to be - generation in an inconvenient location. At one point the National Grid Company, operator of the transmission network in England and Wales, even declared that the rise of smaller-scale generation might endanger system stability, and that the central dispatchers might have to be given control over generators down to 10MW of output. In outraged rejection of this idea, smaller generators pointed out that the real stability problem rested with large steam-cycle units that could trip and send a 500MW transient hundreds of kilometers; small generators, comparable in size to loads, could have no such drastic impact. The stability argument seems to have faded into the background; but the traditional mind-set persists. Some traditionalists continue, for example, to insist that all so-called 'intermittent' generation, such as wind, should have to provide full-capacity 'backup' from dispatchable fuel-based generation. Despite such impediments, as smaller-scale generators gradually establish themselves, the description 'embedded' is being supplanted by 'distributed'. Until recently, however, the changes in network arrangements to accommodate distributed generation have been mostly marginal and tentative, frustrating and discouraging for prospective developers of innovative generation of whatever kind.

A more promising approach, once again pioneered in the US, adopts the catchphrase of computer users, 'plug and play'. Computer hardware said to be 'plug and play', as the phrase indicates, conforms to a standard technical protocol; it can be connected to the rest of the system with no further specific preparation, and will forthwith function as desired, as a part of the system. For electrical hardware, loads such as lamps, motors and electronics have long been 'plug and play'. So long as a device meets the requisite safety and other standards, it can be connected to a traditional synchronized AC network, indeed plugged into a socket, and turned on immediately. Generators, however, have never been traditionally accepted on the same basis. Under the traditional monopoly franchise, a user might well have, say, a standby diesel generator for emergencies; but it could be used only in isolation, with the user's on-site system disconnected from the network. Any generator intended to operate continuously while connected to the network had to satisfy not only the requisite electrical-engineering protocols for basic safety and performance but also operational protocols laid down by the network operator, restricting its use. In traditional electricity the system did all in its considerable power to obstruct and if possible prevent on-site generation and cogeneration. After liberalization, this obstructiveness was supposed to give way to competition between generators on a level playing-field. But networks have yet to welcome small-scale and on-site generation with anything but severely modified rapture. To date they have had little if any incentive to do otherwise.

Encouraging signs are nevertheless perceptible. In the UK, for instance, an 'Embedded

Generation Working Group' reported in 2001, and its key recommendation led to the establishment of a 'Distributed Generation Coordinating Group'; the change of designation from 'embedded' to 'distributed' was itself noteworthy. This group, including high-level participants from large and small generators, network owners and operators, users, regulators, consultants and government, in turn reported in March 2004. Expressing collective satisfaction with progress, the report indicated a forward programme of further efforts to eliminate barriers to distributed generation, and indeed to provide incentives to distribution network operators to foster it. The detailed analysis undertaken by and for the group is impressively comprehensive, addressing a wide spectrum of issues affecting the status and prospects for innovative generation connected to networks at lower voltages and closer to users. As yet, pending the establishment of the promised incentives to network operators, the achievements can mainly be characterized as clearing the decks, removing actual obstructions; but that in itself is an essential preliminary. True 'plug and play' for small-scale generators - which EU discussions call 'fit and inform', requiring no prior permission from the distribution network operator - is farther down the line, but the group considers it possible by 2006. The group is also considering longer-term network concepts and options. It notes that 'Significant increases in distributed generation will fundamentally affect the design of distribution networks'. For 'design' you could read 'design and operation', or simply 'function'. The rise of small-scale local generation, and of optimized local systems closely linking generation and loads, will interact profoundly with the neighbouring network, as will be discussed below.

The UK exercise is also valuable and instructive in that it brings together network regulators with all those who use the network and rely on it, an opportunity to pursue in depth the question that opened this Working Paper: what is the network for? What should it be for as electricity evolves, and how should regulation help the network to evolve appropriately? In the longer term, what will the network look like, and how will it work? At the moment, for instance, 'transmission' and 'distribution' are useful descriptions of distinct subsections of the network, with distinct ownership, financial arrangements and regulatory frameworks. Will that continue? To all these questions we can decide the answers; none are predetermined. If policymakers - especially regulators - weigh long-term network options with open minds and imagination, change could accelerate dramatically.

For obvious reasons, changing the technical configuration of the network toward one more amenable to decentralized generation will necessarily be a gradual and protracted process. It will only happen if financial arrangements and institutional frameworks also change; indeed such conceptual and procedural changes are a critical prerequisite for technical change, for actual physical reorganization of network hardware. The financial arrangements that now underpin liberalized electricity continue to focus on the flow of electricity through meters and other measuring instruments in the network, on transactions based on this flow and on the price per unit of electricity as it flows - commodity transactions and a commodity price. Electricity finance continues to treat decentralized small-scale and local generators as equivalent to remote large-scale generators. From this viewpoint what matters is the flow of electricity delivered into the network as a whole, not the electricity delivered to local loads with minimal or zero use of network circuits beyond the local meter.

However, if decentralized generation is to achieve its real potential, it will often become part of an integrated local system, in which generation and loads are optimized together for maximum performance - not on a short-term commodity basis but as an overall investment in system assets to deliver desired services. The flows of electricity into and out of this local system may not be trivial, but they will be of secondary importance to the overall financial status of the local system. The advantages of such an integrated local system are manifold. Designers, operators and users of this local system would have direct and immediate interest in combining and integrating system assets, especially loads, to get the best available performance, for reasons of economics, reliability and security, to keep the local lights on. The cumulative effect of such integrated local systems would be a dramatic increase in the effectiveness of the energy infrastructure, reducing both dependence on fuel and vulnerability to disruption.

One early move to support a transition in this direction would be to broaden the financial relationship between the generator and the wider network - a change that could be introduced almost immediately, and with ample precedent. In traditional electricity, users with loads have long paid a two-part or 'binary' tariff, described as a fixed charge for the connection plus a variable charge for the amount of electricity used. In effect the user is paying the fixed charge in order to have the system assets, in particular the network, available when required. A financial arrangement of this kind, taken for granted for loads, could well be extended to apply to generators, especially if the generators are broadly comparable in size to loads. In recent years some companies owning and operating large generating stations in competitive markets such as the UK have lobbied vigorously for so-called 'capacity payments' - payments for keeping generating assets available, whether or not they are actually delivering electricity at any given time. Regulators argue that that such fixed payments unconnected to flows of electricity would undermine the electricity market, in which transactions all depend on trading quantified units of electricity at a quantified price. But owner-operators of traditional power stations point out that they get paid only when the station is delivering electricity; that - unlike a genuine commodity such as wheat, oil or pork bellies - they cannot store a station's output until it can be sold at an acceptable price; and that the nature of the market is such that unit electricity prices may be too low even to cover the owner-operator's cost of capital, which has to be paid whether or not the station is generating. In consequence a lengthening list of major UK power stations is in acute financial distress; some foreign owners have simply walked away, leaving stations in the hands of creditors. In any case, the price paid by electricity users is determined in substantial part not by the market but by the charges for use of the network. These charges are set by the regulator, and paid by users who remain in this respect captive customers exactly as before liberalization. In such a context absolute insistence on a pure commodity market in electricity is ideological, not practical. It appears less and less likely to deliver stable or reliable long-term electricity services.

A key aspect of the problem may be simply the long-standing conviction that the objective of liberalization and its attendant regulation is to achieve the lowest possible unit price for electricity. Regulators have taken that objective as self-evident, and congratulated themselves on progress in that direction. Large users, especially electricity-intensive industries, have broadly agreed. But most electricity users, including households and small businesses, appear to have little idea of the unit price of electricity, nor do they much care. What matters to them, what they want, is not a lower unit price but a lower bill. The one does not necessarily imply the other. Intriguing recent research, indeed, suggests that a higher unit price may actually lead to a lower bill, by encouraging upgrading of end-use equipment. At the very least, regulators should reappraise the underlying objective, and ask whether a low unit price is either necessary or even desirable, given its corollary implications on generators and users alike, for reliability, security, efficiency and environmental impact.

Questioning the desirability of a low unit electricity price does not imply questioning the desirability of a market. What is in question is not the idea of a market, but the nature of this market - what is being bought and sold, by whom and how. Since liberalization, the electricity market has been modelled mainly on the market for natural gas; but it need not be. Suitable transactions need not be confined to trading in defined quantities of electricity over defined time periods at agreed prices. Contracts could readily be redrafted to include, for instance, payments for availability of assets, or to reserve capacity of assets, at fixed prices with no reference to flows of electricity, if both counterparties so desired - provided the regulator agreed. Nor need counterparties be, for instance, a generator and a user, as would normally be the case for a commodity transaction. Indeed network owner-operators might become active participants. In appropriate circumstances, moreover, an asset-based contract could also include network assets. That would become yet more important with the significant emergence of private wires as important circuits within the wider network. Such possibilities also suggest a wider and more creative role for the regulator in helping to shape contractual agreements, to identify and incorporate appropriate incentives to foster innovative electricity in all its varied manifestations.

For that to happen, the regulator must have the requisite authority and backing from the relevant government. That in turn means that the government must have an adequate understanding of the true range of technical, financial and institutional options and choices, both traditional and innovative, available to electricity policy. Government will have its own objectives for electricity: first and foremost to keep the lights on, to do so reliably over time at acceptable cost and with acceptable environmental impact. Government will have to decide how best to achieve these potentially competing objectives. In a liberalized context, however, except when it acts on its own behalf as an electricity user, it cannot directly implement electricity policy, in the sense of investment or pricing. Instead it must set the legal and regulatory framework, and wait to see whether other players act appropriately. In the present transition phase beyond traditional electricity, government still has significant leverage, through taxation, grants and other financial measures, standards for performance of assets including buildings, and its own procurement policy. It can also give guidance to the regulator, particularly over networks that remain more or less unbroken political monopolies. But governments in general tend to leave such specialized matters to the regulator, requiring only the regulator's assurance that the lights will stay on. As and when such assurance cannot be given - or proves mistaken - governments will face a severe challenge. They would do well to study the electricity options - all the options, innovative as well as traditional, accurately evaluated and compared - beforehand, when they can act rather than react.

As they do, they might well raise their sights beyond the next election. Governments genuinely desiring the most reliable, economic and sustainable electricity services for their citizens in the long term now have an unparalleled opportunity within their grasp. All over the world, governments have endorsed the global aspiration to sustainable development. Many have also committed themselves to reduce emissions of greenhouse gases, particularly carbon dioxide from fossil fuels. A rapidly expanding body of evidence indicates that a key dimension of sustainable development will be sustainable energy; and the centrepiece of sustainable energy will be sustainable electricity. No one can yet be sure what sustainable electricity will look like. But any dispassionate observer can recognize unsustainable electricity. It looks like the electricity that now powers most of the planet. It is generated far from loads, by large dams and fossil-fired and nuclear steam-cycle stations, and delivered as synchronized AC over networks including long high-voltage transmission lines. It is unsustainable for several cogent reasons. It has long since failed to reach one-third of humanity - some two billion people - and may now be losing, not gaining, ground. In a liberalized framework its key generating technologies are all seriously risky to finance, even in OECD countries, and raise environmental problems that may become insuperable. Its technical configuration, as a single gigantic machine operating in real time, is inherently vulnerable to disruption over a wide area and almost instantaneously, not only by mishap but also by malevolence. It cannot deliver either the reliability or the power quality that many sensitive loads now demand. Nor is it the optimum way to deliver electricity services to rural areas as yet unserved, with a widely dispersed population and low load density. Nowhere in the world can you now see an electricity system that appears comprehensively stable, satisfactory and secure. In such a context, today's official electricity policy tends to feel either like wishful thinking or like fire-fighting, endeavouring to forestall calamity.

Consider, then, a possible long-term alternative, as updated from the author's book *Transforming Electricity* (RIIA/Earthscan 1999), as a thought experiment. Using only technology that already works, but that may at the moment be considered too costly, can you devise a system in which all electricity services now required are provided with a maximum of reliability and a minimum of environmental impact? Remember that what we want is the services - illumination, comfort, motive power, refrigeration, information-handling and so on - not the electricity. If we can get the same or better services more reliably with less electricity, fine.

A high-reliability, low-impact system might look something like this. All buildings are designed and constructed to take maximum advantage of natural ambient energy flows, including light, heat, and convection currents of air. Daylight reaches much of the interior of a building. The building structure acts as a heat store, soaking up excess heat or releasing stored heat, to keep the interior at a comfortable temperature whatever the temperature outside. Air circulates throughout the building gently and continuously, because of its interior layout and the small temperature differences between various parts of the building. A rapidly growing number of modern buildings in many parts of the world are already based on these principles - as, indeed, are many very old buildings, constructed before electricity became an option, when builders made skilled and subtle practical use of the light, heat and air circulation naturally available.

Since the building itself provides much of the illumination and comfort required, electricity has much less to do to augment these services. The interior illumination comes from high-efficiency lighting, including compact fluorescent lamps for all lights that are on more than briefly, or are in awkward locations in which burned-out incandescents would need frequent replacement. Well-designed fittings direct the light to where it is wanted, with minimum waste. In temperate and tropical climates, buildings appropriately designed and constructed can maintain comfortable interior temperatures with little or no assistance from electricity; a requirement for significant active air-conditioning is a symptom of a badly-designed building. In cold climates, however, when outdoor winter temperatures are well below freezing, additional interior warmth is provided by microcogeneration or by electric heat pumps, already common for instance in Scandinavia. Buildings are also equipped with sensors that measure temperature, light levels, occupancy and other relevant information, and with controls that automatically adjust the comfort and illumination to the levels desired.

Inside buildings, two further categories of electricity service are particularly important, motive power and information-handling. Motive power is delivered by electric motors. They are the appropriate size, not oversized as is otherwise common, and equipped with variable-speed drives to maximize efficiency over most of their operating range. Furthermore the equipment they drive is also appropriately sized. Fans and pumps, for instance, are integrated into ducts and pipes laid out to minimize frictional and other losses. The fans and pumps can therefore be smaller, and so can the motors to drive them. Improved system design, integrating and optimizing the performance of all components together, achieves better results at lower cost. The high-reliability low-impact system takes the principle of integrated whole-system design as fundamental, for all buildings and process plant.

Information, including communications, data-processing and entertainment, is handled by electronics. Telephones, faxes, computers, television, video, building controls and security systems are all linked together by digital networks, not only within individual buildings but across cities, countries and continents. Like electric motors, electronics are designed to optimize performance and minimize losses. One design feature is unexpectedly notable. The stand-by mode for electronic equipment, such as the red light that stays glowing on the television when you use the remote control to turn it off, is a surprisingly heavy user of electricity in modern society. In the high-reliability low-impact system, alternative design of standby modes reduces this insidious drain on electricity to a much lower level. Moreover, many people just turn things off completely when they are not in use.

Buildings, lighting, motors and electronics all contribute to delivering electricity services; but they still need electricity to run them. In the high-reliability low-impact system, much of this electricity is generated in or near the place it is used, minimizing vulnerability to disruption. Buildings have gas engines, microturbines or fuel cells in the basement, fueled by natural gas. Some of these units, and others using Stirling engines, operate in cogeneration mode, delivering both electricity and heat. Industrial sites needing heat also use cogeneration, sometimes including not only gas turbines but also steam turbines. Some cogeneration plants use not natural gas but coal, biomass or residue fuel such as refinery sludge, processed in a gasifier to turn it into combustible fuel gas for a gas turbine, or in a fluidized-bed combustor that burns awkward fuels with acceptably low emissions. Some sites such as supermarkets that require heavy-duty refrigeration use not cogeneration but trigeneration, delivering not only electricity and heat but also ice-water for chillers. In suitable applications, trigeneration raises overall fuel efficiency yet higher.

Many buildings also have roofs and facades made of photovoltaic tiles. Buildings using fuel cells and photovoltaics have separate wiring to carry the direct current (DC) these generators produce, to power the electronics in the building. Electronic equipment always requires DC. Delivering it directly avoids the losses involved in converting AC to DC and vice versa. Moreover DC does not carry the disturbances or ‘spikes’ common with AC, that can damage or destroy electronics. Delivering DC also eliminates the cost, weight and energy losses of the ‘power pack’ in the electronics, the transformer and other components to convert AC to the low-voltage DC the electronics actually require.

A local system of wiring and controls links on-site generation to the electrical equipment on the site. Local systems in turn are connected to a wider network that includes larger generators, notably large old hydro plants and modern microhydro units, as well as larger cogenerators, offshore wind plants and some generators in rural areas, such as village-scale biomass power plants. The wider network has some sections operating as synchronized AC. But it also includes many AC-DC-AC links, using power electronics to transfer electrical energy while blocking AC disturbances. The wider network is also heavily instrumented, and carries continuous real-time two-way information, not only about flows of electricity but also about flows of value through the network. The instrumentation keeps the network stable, controlling not only generators but also suitably flexible loads, also instrumented with embedded microprocessors and other controls. Instead of always increasing generation to follow load, the instrumentation may also reduce or disconnect flexible loads to follow generation, as appropriate. It also keeps track of network services, who is providing them and who is using them - who pays and is paid, and how much. Remote rural areas are not, however, connected to this network. They rely on self-contained local systems, that may include biomass power, wind power, photovoltaics and possibly batteries for storage, as well as appropriate system monitoring and control, also local.

In this high-reliability low-impact system, all the technologies described already exist. Such a system is already technically feasible. The network is still there, to provide back-up and arbitrage, and help ensure competitive pricing, on either a commodity basis or an asset basis. However, by minimizing reliance on remote generation by large-scale hydro, coal-fired and nuclear power, and long-distance transmission, this configuration reduces both vulnerability to disruption and the traditional environmental impact of electricity. Indeed it is not an 'electricity system' but a 'services system', with contracts and prices to match. As a thought experiment, such a system therefore appears attractive. But it is still a thought experiment, a long way from reality. The reason is not technical, nor is it primarily one of cost, although cost is certainly a factor. The reason is fundamentally structural. The difference between the structure of existing electricity systems and that of a possible high-reliability low-impact system is profound.

The technical, institutional and financial configurations of existing electricity systems reinforce each other. Any possible alternative configuration starts at a deep disadvantage. Even the anticipated costs of alternatives are assessed according to criteria used for existing systems, which may be completely inappropriate in the alternative context. For example, comparing the cost of electricity from a remote coal-fired power station with the cost of electricity from a photovoltaic roof on the building where it is to be used, without mentioning location, time of day and year, accounting basis or other system costs and risks, including the risk of disruption, is a grossly distorted comparison. But such comparisons have long been used to dismiss innovative generating technologies, by assuming they must fit into existing systems in the existing context. In any case, you must also ask 'The cost to whom? On what financial basis? Who carries the risks? Who pays for the environmental impacts?' Until such distortions are rectified, innovative technologies and configurations will always be undervalued and underestimated by traditional assessment procedures.

The structural problem, however, goes deeper than biased comparisons and distorted decision-making. The high-reliability low-impact system described above embraces all the hardware that delivers the services, even including the buildings - not just the electrical hardware. Envisaging such a system may take us part of the way towards a picture of sustainable electricity; but it omits many salient aspects - especially the institutional. As yet we simply do not know how decisions would be made in such a system. We can anticipate only that many important decisions would no longer be made centrally, or at a national level. Both local and international levels would play a much larger part in essential decisions about electricity than has hitherto been the case.

As the high-reliability low-impact system suggests, sustainable electricity may actually play a substantially smaller role in society, because services previously delivered by electricity no longer require it, or require much less. Indeed, in due course, electricity generated, say, by a photovoltaic roof, and used on the same premises, may not even be measured in official energy statistics, any more than the daylight and body heat and other on-site energy sources that simply arrive and contribute their services. This kind of change is not merely an alteration of the structure of the electricity system. Sustainable electricity means a radical change not only in physical structures but in the way we think about electricity.

‘Sustainable’ implies not only environmentally and socially sustainable, but also economically and financially sustainable, and for everyone everywhere. If sustainability is therefore construed as a counsel of perfection, it will be unachievable. It can only emerge gradually, in electricity as in every other aspect. Minds, however, can change rapidly. If people stop taking the existing structure of electricity for granted, begin to examine and question it, and come to feel that an alternative structure would be preferable, this change of mind will have a fundamental effect on decisions taken from then on. If decisions are made not by some central authority but by a wide range of participants with varied interests, who see electricity differently, the effect may be untidy but dramatic.

In the context of this Working Paper, note particularly the structure and function of the network in this transformed electric future. 'Network' itself now overstates the case; 'networks' would be more accurate. The system is no longer a single synchronized machine operating in real time, but a much more loosely interconnected and interoperating array of significantly independent sub-networks, each with both generation and loads. The networks still produce significant external benefits that grow with size. They may not need to deliver electricity thousands of kilometers; but the possibility to do so if necessary has beneficial effects on local pricing. They also help to smooth and diversify the effects of fluctuating generation as well as fluctuating loads. Early steps in this direction look promising. Work is already under way to devise ways to take advantage of the flexibility of insensitive loads such as refrigerators, freezers and air-conditioners. In the transformed future, instead of 'load-following', systems suitably equipped can 'load-match' by adjusting loads to correspond to generation, not merely vice versa, as appropriate; that may be easier to manage in local systems, but will depend on the particular mix of loads and generators. Within sub-networks, circuits may carry synchronized AC or low-voltage DC as loads require and generators produce, with interconnections using electronics or power electronics as necessary. Between sub-networks, connections may be synchronized AC up to and including high voltage; back-to-back AC-DC-AC; or high-voltage DC as appropriate, again with interconnections using power electronics, including digital transformers, as necessary. The overall shape of the network, its 'topology' or connectedness, will be a mesh, with many nodes and many pathways between them - a sort of 'electricity internet'. Control of voltages and currents through and between circuits will be autonomous, with sensors, instrumentation and switchgear interlinked by telecoms and real-time online processing.

As may be apparent, in this transformed electric future, designating some circuits as 'transmission' and others as 'distribution' will no longer be useful. Network assets, loads and generators may all belong to a single owner, or different owners in various groupings, including for example property-owners. The traditional monopoly franchise will be attenuated or completely eliminated, although some form of regulatory oversight may still be required, to enforce protocols and transactions. Some transactions may still be mediated by meters and measured flows of electricity. Others will be longer-term contractual relationships, such as agreements for availability or reserve of assets, or for services, of a specified quality over a specified period. Payments may be fixed or variable as agreed between parties, with no necessary reference to flows of electricity. Investment in relevant assets will depend on suitable financial arrangements for subsequent revenue from using the assets. Decades hence, when fuel-based generation has dwindled and infrastructure generation ramified, electricity may gradually become not only physically but economically invisible, as yet another function of infrastructure. It will be paid for not by the measured unit but by investing in infrastructure assets. In many circuits the flows of electricity will not be measured at all, because no transaction depends on them, any more than in Edison's day.

If governments find such a long-term vision attractive, and seek to foster electricity with high reliability and low impact, many policy levers are already within their grasp. The crucial shift of focus is away from electricity as a commodity product, to electricity as an asset process. Government policy on asset taxation, asset acountancy, asset grants and financial support, asset regulation, asset standards, asset procurement and asset contracts can all exert valuable pressures and provide potent incentives to move from traditional to innovative electricity. The essential prerequisite is to redefine the framework, to reveal the levers. Governments in turn will have to give appropriate guidance to regulators. Their role in reshaping the system, with focused incentives for participants, will be crucial.

The network is best positioned to lead this transformation. It should foster change, not merely follow it reluctantly. The evolution of the network should trace the same arc as generation: initially to higher voltages, longer distances and more centralization, now back toward lower voltages, shorter distances and decentralization, including integrated optimized local systems. Over time, as infrastructure generation gradually supersedes fuel-based generation, networks too become infrastructure. No one measures electricity, buys it or even notices it. Infrastructure keeps the lights on.