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*Transforming Electricity: Working Paper 4*

# Electricity: Network Futures

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## 1. Introduction: the network dimension

A single electricity generator running a single load requires a single loop of wire to complete the circuit, and a single switch to turn the current flow on and off - think of an electric torch. However, two or more loads require two or more loops, and an increasing array of switches; you have the beginning of a network. Even the simplest central-station electricity system entails a network connecting the generator to multiple loads; a system with a number of generators and many loads entails a network of intricate complexity. The network is an essential, inherent feature of a central-station electricity system. Some estimates indicate that on a typical synchronized AC system the network - cables, towers, trenches, transformers, switchgear, controls, protective devices and so on - may cost as much as the generating plant, perhaps more.

Working Paper 3 focused on the various 'centres' involved in a typical electricity system. This paper in turn will consider the network that links the centres together. How might an electricity network evolve over time, under the pressure of the changes now affecting electricity systems around the world, particularly the various degrees and stages of liberalization? An electricity network gives rise to a range of issues, among them the following:

- terms and conditions for the use of public space;
- procedure for establishing the network;
- role and function of the network;
- choice of network technologies;
- cost of the network itself;
- ownership of the network;
- management of the network;
- operation and maintenance of the network;
- maintenance of stability of the operating network;
- capacity of the network;
- access to the network;
- pricing of network access and services;
- extension of the network;
- environmental impacts of the network; and
- interaction with other networks.

Traditional electricity systems, as described in earlier Working Papers, have resolved these issues in traditional ways, often by direct government intervention. But changing the ground rules for electricity systems raises many of these issues afresh, in altered contexts that may bring both new problems and new opportunities.

In a traditional franchised monopoly electricity system the network is essentially a delivery route, controlled from the centre, to deliver from generators the electricity being purchased and paid for by the users. A user 'places an order' for electricity by connecting equipment to the network. The delivery is effectively instantaneous, the ultimate in 'just-in-time' inventory management, because electricity cannot be stored. The central controller of the system has to ensure that electricity delivered to a user is 'replaced' more or less instantaneously with electricity generated, to keep the flows of electricity through the network stable. That means having the capacity available and under central control to generate the required electricity, both instantaneously and over the longer term. The electricity is paid for after it has been delivered and used, possibly some time after.

The monopoly franchise means that the user can buy electricity only from one seller, the franchise holder; and the user has access only to the one network. The franchise holder also has a corresponding obligation to supply all requirements for electricity in the franchise area. This may entail building not only new generation but also new network facilities. However, in principle at least, a regulated franchised monopoly system is effectively a cost-plus activity. The system fulfils its obligation to supply, and the users are under a corresponding obligation to pay. The cost of constructing, operating and maintaining the network is bundled into the tariff, along with the cost of constructing, operating and maintaining the generating units. In practice, to be sure, franchised monopoly systems in many countries fail to function as cost-plus activities, or to meet their obligation to supply, for political and other reasons, not least the cost and difficulty of extending the network. Such systems may be particularly appropriate candidates for a different approach to electricity networks, as will be discussed below.

On a central-station system, almost all the loads are smaller, often substantially smaller, than almost all the generators. One important role of the network is to mediate between these differences of scale. The network divides up and allocates the large outputs of electricity from each central station. At the same time the network aggregates the many small and varying loads, smoothing them out into a gradually changing overall load on the central stations. If the system is a franchised monopoly, this process is straightforward and taken for granted. If the monopoly is removed, however, the role of the network changes, and intriguing questions arise.

The traditional electricity system used to be called a 'natural monopoly', because of its dependence on a network. The argument is that establishing two different networks of wires in the same area, to be accessed by the same users, is economically inefficient. Whether or not the network itself is genuinely a 'natural' monopoly under all conditions deserves and will receive further discussion below. However, generation clearly is not. Even within a traditional monopoly system, individual generating units actually 'compete' with one another, in the sense that those producing cheaper electricity are dispatched ahead of those producing more expensive electricity. In a liberalized system the competition can become explicit, as a given quantity of electricity is generated over a given period and sold at an agreed price to a known purchaser.

The role of the network is then - at least in principle - to deliver a given quantity of electricity from a particular seller to a particular purchaser, with some sort of charge for the delivery service. Unfortunately, of course, complications arise. If the network were simply transport infrastructure, like a road system, the electricity could be sent onto it at one end and received at the other. However, unlike a road system, waterway or pipeline, an electricity network is not simply transport infrastructure carrying a commodity put into it at one end and taken out at the other. As earlier Working Papers have discussed, an electricity network is part of a single vast machine operating in real time. A synchronized AC system cannot remain stable under conditions of uncontrolled access by individual sellers and purchasers of electricity. Each increase or decrease of load connected to the network has to be matched by an equivalent increase or decrease of generation, and vice versa, on a continuous basis.

For historical reasons, the assumption has always been that users are free to connect loads to the network, and that the rest of the system, in particular the generators, are constrained to respond accordingly, under central control. The network itself does not in fact have to operate in this mode, so long as the essential 'balancing' of loads and generation can be assured. If loads and generators were of equivalent size, each new load and each new generator could be connected simultaneously, and disconnected likewise. In principle, in broad-brush terms, a purchaser could arrange to connect a load of a certain size at a certain moment agreed with a seller who connected the same amount of generation at the same moment, with no reference to the central controller, without destabilizing the system. Put in those terms the idea sounds far-fetched; but information technology will soon make it much less so. The more immediate problem is the mismatch of scale between units of generation and units of load. As Working Paper 3 argued, that mismatch may become less pronounced. The point is raised here only to suggest that traditional assumptions about the role and function of various parts of an electricity system, and in particular the network, may not be inviolable as circumstances change. Previous Working Papers examined the possible implications of internationalization, liberalization and decentralization of electricity systems. This paper will explore some of the implications for electricity networks.

## 2. Electricity and interactions

Human society abounds in networks, metaphorical and actual. A network is a pattern of interconnections between points of interest - people, places, technologies and so on. Each point at which interconnections meet is a so-called 'node' on the network. Of particular interest here is what happens along the interconnections - the interactions between the nodes. A network is a potent metaphor. Consider, for instance, the now-familiar expression referring to a 'network' of friends and colleagues, and some of the attributes of such a network.

- Within the network, the flows along the interconnections may be information, goods and services.
- The network is established ad hoc.
- Anyone in the network can initiate connections, or terminate them.
- A network of people evolves continuously; individual people can join the network or leave it at will, or their status may be indeterminate.
- Access to the network may entail transaction costs, but is otherwise free.
- No single participant controls the network.

- Its boundaries and its structure are likely to be fluid, diffuse, imprecise and continuously evolving
- A map of such a network is always at best a rough approximation, inevitably omitting relevant interconnections and nodes.
- No outside observer can keep hope to keep track of all the interconnections in the network as it functions.

At first glance the foregoing may appear to have little to do with electricity. But it serves to identify and highlight significant attributes that characterize a network, and distinguish one type of network from another. It also describes a network that is in crucial respects the antithesis of the network involved in a synchronized AC electricity system. The nodes on a synchronized AC network are technological devices that generate, convert or use electricity. As you might expect, key attributes of this network differ markedly from those of a network of people.

- The flows along the interconnections - the interactions - are electric currents. They carry information that may or may not be retrieved. By driving electrical devices they deliver physical services. Some analysts now regard electric currents as 'commodities' or goods.
- The network must be established through a lengthy and complex process of planning, permitting, finance, construction and testing before any interaction through it is possible.
- By historical convention, only electricity users are free to to connect to or disconnect from the network moment by moment. Generators and converters are constrained to respond accordingly, if the system is to remain stable.
- An electricity network evolves in steps. Electricity users can leave the network at will, but must have authorization to join it. Those who join without authorization, to 'steal' electricity, as happens in many non-OECD systems, represent a major problem. Generators can leave the network inadvertently, by unplanned outage; but all generators above a certain size must otherwise join or leave the network under the direction of the central controller, to maintain system stability.
- Because establishing and operating the network is expensive, access to it for both users and generators carries a cost, usually in the form of a connection charge of some kind, except when the owner of the network also owns the generator.
- The network is under the ultimate control of a single central controller responsible for keeping the system stable.
- The boundaries and structure of the network are sharply defined out to users' meters and sometimes beyond. Changes have to be explicit and authorized.
- The central controller must have a comprehensive map of the network and its nodes, although small loads and their interactions may be aggregated.
- The central controller has to keep track, directly or indirectly, of all but the small aggregated interactions in the network as it functions.

The network of a synchronized AC electricity system thus imposes stringent constraints on everything connected to it and everyone using it. Because these constraints have evolved for many decades, they have long since been taken for granted by system users and operators alike. But they make the electricity network fundamentally different not only from metaphorical networks of people but also from the many other physical networks that crisscross modern society - roads, railways, waterways, gas grids, telecommunications and so on. Roads, railways and waterways are interconnecting pathways carrying traffic; the traffic on any particular pathway has at most a limited and delayed interaction with traffic elsewhere, mainly if the carrying capacity of the pathways is close to saturation, causing congestion. The same is true for telecommunications, although the 'pathways' in question are frequency bands, either in wires or in space. Water-pipe networks and gas-pipe networks, too, are interconnecting pathways; pressures and flows in one part of the network can interact with those in another part of the network, but only gradually and with cumulative buffering effect over distance. The interactions within a synchronized AC network are, by contrast, complex and non-linear and can be very nearly instantaneous, even over distances of thousands of kilometres. That is why a synchronized AC electricity system can legitimately be characterized as a single vast machine. It is also why the control structure, constraints on access and other attributes of the system network have to be so stringent.

Such an arrangement, of course, is entirely apt for a centrally-controlled monopoly. The operational status of the network moment by moment can be overseen and directed from the centre; so can the gradual evolution of the system, as generation and network components are added and subtracted. Even a moderate degree of liberalization can be accommodated, such as independent power producers (IPPs) subject to central dispatch, and indeed to dispatch accordingly to the prices they bid - provided that the central controller retains the requisite authority over dispatch and access to the network; see Working Paper 2. Matters become somewhat less clear if liberalization extends to bilateral contracts between generators and users, both relying on the network to carry their interaction. On one level this appears to be directly parallel to the traditional arrangement, whereby the network is just a delivery route transporting the output of the generator to the user buying it. But on a synchronized AC system the interaction between this particular bilateral transaction and the many others also passing through the network is not merely additive but multiplicative and non-linear, even on a network with ample carrying capacity. The real-time processes involved in keeping network operation stable - not merely matching loads and generation but also controlling voltage and frequency, balancing reactive power, keeping track of loop flows of current through unexpected pathways in the network, and coping with disturbances - are not easy to disentangle, nor are the relevant responsibilities and costs.

As long as the processes can be directed from the centre, and the costs aggregated and allocated acceptably from the centre, the system can continue to function. Where liberalization is in progress, however, weakening the authority of the centre, uncertainties enter and proliferate. Even if the central authority backed by government is weakened, keeping the system in stable operation is clearly in the interest of all participants. Nevertheless competition, both between generators and between companies selling electricity services to customers, may lead to disputes over use of and access to the network; and the network is very vulnerable to disruption.

In a more liberal context, therefore, a much more wide-ranging pattern of interactions between system participants must be anticipated. As earlier Working Papers have already argued, decisions significantly affecting the immediate status and longer-term evolution of the system can no longer necessarily be determined ultimately from the centre. For networks in particular, the issues listed in subsection 1 above may re-emerge, in potentially more controversial forms, presenting new challenges both to existing mature networks and to those already struggling to cope with overloaded and inadequate capacity. In a more liberal context, for instance, the following points have to be addressed:

- explicit and defensible terms and conditions for access to the network by electricity users;
- explicit and defensible terms and conditions for access to the network by generators;
- expanding and otherwise altering the network - who is to decide, who is to implement, who is to pay;
- investment in the network - how and by whom, with what return, how determined; and
- links and interactions between the electricity network and other networks, including gas networks and telecommunications.

The prevailing assumption appears to be that electricity networks will continue to expand indefinitely, within the same overall technical configuration, as an inevitable corollary of inexorably increasing electricity use everywhere. As subsequent sections of this paper will discuss, this assumption may prove to be wrong.

## 3. Networks and electricity finance

Existing electricity networks originated as an essential concomitant of central-station generation. They were set up and paid for accordingly, either by entrepreneurs or by local governments, with electricity users thereafter paying tariffs covering the cost of establishing and maintaining the network. Governments were always involved in any case, because networks had to have permission to use public space. In due course, this was one consideration that encouraged governments to grant monopoly franchises for central-station systems, to minimize the proliferation of intrusive physical networks. The monopoly franchise in turn became a fundamentally important factor in financing the expansion of systems and their networks. As electricity became progressively more desirable, the monopoly franchise meant that all prospective customers in the franchise area would have to purchase their electricity from the franchise holder, effectively guaranteeing a revenue stream and a return on the required investment. As economies of scale in generation brought down the cost, more and more customers demanded more and more electricity. Both generation and networks expanded. As central stations grew ever larger, transmission lines grew ever longer, with ever higher capacity. The investments involved were impressive, but not the risks - not, at least, for the financial backers. The monopoly franchise saw to that.

Great stress was - and still is - laid on the argument that an electricity network is a ‘natural monopoly’. To have two sets of wires to the same premises, competing for the same custom, is economically inefficient, so the argument goes. Why the ‘natural monopoly’ should also be made a legal monopoly is less obvious. If some other entrepreneur is prepared to take the risk of installing a second set of wires to compete with the incumbent set, why should the government prevent this? It may of course be defending its own monopoly system - not necessarily a persuasive argument. The question of intrusion in public space is now surely academic, as electricity, gas, water and telecoms companies take turns to dig up urban streets. However, one argument does carry some force: allowing a second network to compete with the first could financially cripple both, to the detriment of customers and service. If both networks are not only serving the same customers but also delivering the same identical commodity, this aspect of the 'natural monopoly' argument makes sense. In the 1990s, nevertheless, parallel networks are competing for the same customers in many locations where cable telecommunications companies are operating. The cable companies are installing networks that may compete directly with those of the existing monopoly telephone company. In this case the 'natural monopoly' argument appears to have been circumvented because the cable companies are offering services that differ in some essential details from those offered by the existing telephone monopoly. In due course something similar may happen to the 'natural monopoly' argument as applied to electricity networks, especially if new business opportunities supplant the common and misleading presumption that electricity is a commodity, as Working Paper 5 will discuss. Indeed, over time, delivering electricity services supported by information technology may lead to significant convergence between telecommunications networks and electricity networks, further weakening any remaining monopoly on either side.

Be that as it may, financing a monopoly network is not a problem. The same, however, cannot so readily be said about financing a network that does not have a monopoly franchise. Unlike a generating station, an electricity network itself appears to earn no revenue. It is inherent in the central-station model of electricity system; but the longer and more elaborate the network, the more it costs to set up, to operate and to maintain. In the traditional monopoly-franchise model the network can perhaps be regarded as a kind of capital extension of the generating units, right to the user's meter. As suggested earlier, it is a delivery route to carry electricity from seller to purchaser, and the extra cost of a longer network is - at least supposedly - offset by the cheaper generation at the more remote location. The costs of generation, transmission and distribution are aggregated into a tariff set by some process that regulates the entire monopoly system. The costs of transmission and distribution are not explicitly separated in the tariff, and may well not be tracked within the system itself, at least not assiduously. Whatever the costs, the users will bear them.

An early stage of liberalization, in many places where it is in progress, is therefore to 'unbundle' the costs of generation from those of the network, and indeed to unbundle the costs of high-voltage transmission from those of low-voltage distribution. Some processes, such as that in the UK, also unbundle the cost of customer service itself - metering, billing and so on - calling this 'supply', a term open to misconstruction by the unwary. A corollary of this unbundling is the need to establish an agreed basis for identifying the costs to be associated with the network and the services it provides. The operating costs - staff salaries and wages, spare parts and so on - can be identified unambiguously. But ambiguities arise in the accounting procedures chosen to assign value to the capital assets the network represents. The investment that set up these assets, under conditions of vertical integration and monopoly franchise, is a sunk cost. But it has a book value, written down by whatever depreciation has been considered appropriate.

What asset value is to be used as a basis to calculate the appropriate return on these assets, as a component of a tariff? Should it be the written-down book value, or the notional 'replacement value', the current cost of replacing the system? Yet another option arises if a government sells a network to private investors. Is not the appropriate asset value then the sum paid by the private investors at the time of the sale? Even in a liberal competitive framework, if the network itself remains a franchised monopoly, this ambiguity has to be resolved by the regulator, more or less arbitrarily, to no one's complete satisfaction.

More challenging still in a competitive framework is the question of evaluating a whole range of system services necessary to keep the network stable. The IEA report *Electricity Supply Industry* (1994) lists the services for which appropriate prices and a procedure for payment must be established. They include:

- energy in units of electricity;
- capacity or maximum output from a generator;
- voltage support;
- frequency support;
- off-peak load for inflexible base-load generators;
- spinning reserve - generators sychronized to the network but delivering no power, ready to provide rapid replacement for any generator that fails;
- load-following capability - generators that can increase or decrease output rapidly, to match changes of load;
- black start capability - the ability to start up without using system power;
- dual fuel capability; and
- local load - the ability to deliver electricity locally without passing through the high-voltage transmission network.

Assigning prices to all these various services, and identifying who is to pay whom on what basis, is a task of daunting intricacy. To the extent that it has thus far been taken up, it has become the de facto responsibility of the regulator, who may or may not pursue it in detail. If liberalization leads to increasing decentralization, as earlier Working Papers have suggested, the task may become yet more onerous, and more difficult to carry out. To the extent that the task is ignored, some system participants will gain services for which they do not pay, and others will deliver services for which they are not paid. Those who are not paid may become less willing to deliver the services. Over time, system margins may tighten and network stability may grow more precarious. As Working Paper 3 has argued, users may respond accordingly, by reducing their dependence on the system and relaxing their integration with the network.

A somewhat analogous situation may arise where networks are already unable to deliver a reliable - or indeed any - service, notably in a variety of mainly non-OECD countries. Where network electricity is chronically unreliable, as is the case, for instance, in many parts of India, major industrial users now frequently prefer to generate their own electricity on-site. For an engineering company, negotiating a contract with a single major user for on-site generation may be easier than negotiating a power purchase agreement for IPP electricity with a government-owned electricity system, with its political agenda. As shortage of capital and revenue forces government-owned systems to liberalize and relax their central control, on-site generators may come to supply not only their own requirements but those of neighbouring sites, especially if on-site generators are built and operated by international companies who specialize in such contract activities. In such a context, the option of building a new, dedicated network to deliver electricity locally, rather than relying on the overloaded and sometimes mismanaged existing network, may well prove attractive. A complete local system, including network, would undoubtedly be politically acutely controversial, not least because it would threaten to bypass the local political machine, for which the existing electricity system is rich in patronage. Nevertheless, if it were being installed at the instigation of major local industries and industrial employers, political opposition might be overridden. Financing such a local system might actually be comparatively easy, on the basis that tariffs would not be unrealistically low, customers would pay their bills and no one would steal electricity.

In some places electricity networks are unreliable; in many others they are non-existent. Extending synchronized AC networks into localities comparatively thinly populated, where even the potential density of load is low, has always been disproportionately if not prohibitively expensive. In North America and many parts of Europe, rural electrification by extending synchronized AC networks has always been subsidized, either directly by governments from taxpayers or indirectly by electricity system tariff structures, for basically political reasons. In non-OECD countries whose rural areas are not only thinly populated but poor, extending the synchronized AC network is often simply out of the question, both logistically and financially. In this context, local network systems may be the answer. Until recently, local systems have attracted little financial support from international funding sources, which have preferred to back centralized mega-projects. That outlook may now be beginning to change, although as yet practical evidence of the change is limited. In the meantime electricity organizations such as ESKOM in South Africa and National Power Corporation (Napocor) in the Philippines, conceding that a sizeable rural population cannot be reached by the central-station network, have embarked on substantial programmes of village-level electrification based on local generation and local networks. If these programmes succeed, they may be widely emulated elsewhere - possibly even in OECD countries.

One important and potentially controversial aspect of networks and electricity finance arises not from financing the network, but from the influence of the network on the finances of those using it. As indicated in earlier Working Papers, the revenue stream earned by a generator will depend on being able to use the network to deliver its output to paying customers. In a liberal context, in which individual generators may belong to different owners and have contracts with particular purchasers, access to the network - that is, dispatching, on a synchronized AC system - will be essential. At this early stage of liberalization even on systems where the process is comparatively well advanced, the eventual implications of the network-access issue are difficult to foresee. For the moment, a carryover of ‘public service’ culture, combined with generous short-term revenues, adequate system redundancy and only limited competition, have held off the day of reckoning. Somewhere down the line, nevertheless, some independent system operator (ISO) trying to keep a system stable will almost certainly face the probably litigious wrath of generators and users whose contractual arrangements get caught up in a network bottleneck between them.

One other aspect of networks and electricity finance has recently developed intriguing ramifications - the emerging and strengthening link between electricity networks and other networks, in particular those for gas and for telecommunications. Links between gas and electricity are of course nothing new. Many investor-owned companies in the US, for instance, sell both gas and electricity and have done so for many decades. More recently, privatized companies in the UK are starting to do likewise; and the same is true elsewhere. What is novel is the interlinked role of the two networks.

Historically, gas systems and electricity systems, even when they belong to the same owner, have been physically separate systems, each operating independently of the other, each financed independently. Until the 1980s, natural gas used to generate electricity was almost always simply burned as boiler fuel, to raise steam for a turboalternator. The practice arose originally because natural gas emerging from an oilfield was then regarded as a nuisance or worse; piping it into a single large power station boiler and burning it to raise steam was almost a form of waste-disposal, more elaborate than flaring but still pretty much an afterthought. When natural gas was recognized as a desirable fuel in its own right, and distribution networks were established or converted to deliver it profitably to large numbers of smaller-scale users, gas-fired power station boilers lost their commercial edge. To be sure, existing plants continued to operate, and still do, notably in some parts of the US. Elsewhere, particularly where gas was abundant and prices artificially and arbitrarily low, for instance in Soviet Russia and Romania, many large-scale gas-boiler cogeneration plants were built to supply both electricity and heat. But the advent of the gas turbine in the 1980s, coupled with the surging abundance of natural gas, created a much more positively attractive package for electricity generation.

The combined-cycle gas turbine (CCGT) station has a much higher fuel efficiency than the gas-fired boiler. Even when paying a commercially competitive price for natural gas, a CCGT station can therefore generate electricity at a competitive price. In the 1990s, as earlier Working Papers have noted, CCGTs have become the technology of choice for new generating capacity wherever natural gas is available. The consequences for networks and electricity finance are manifold. In localities where both gas and electricity networks already exist, for instance many OECD countries, natural gas energy can be delivered to users either directly or in the form of electricity. In a liberal context, entrepreneurs with access to the relevant resources and technology can profit by arbitrage between the two networks, buying and selling natural gas or electricity according to whichever attracts the better price at any given time. In the same liberal context, however, this possibility could cause trouble. In temperate climates the peak load on electricity systems may coincide with that on gas systems, driving up prices for both electricity and gas. If both systems are operating close to their margins, switching gas supplies from electricity generation to direct sales at short notice may create stability problems for the electricity network. In the UK, interruptible gas-supply contracts to power stations have already threatened similar consequences at least once. Regulators and central controllers of electricity systems will have to keep a close eye on the linkages, contractual and otherwise, between electricity networks and the gas networks that supply an increasing proportion of their fuel.

Where gas networks do not yet exist, electricity networks may, paradoxically, help to foster them. The infrastructure for gas production and transmission represents a massive front-loaded capital investment, whether it entails pipelines or LNG facilities. Undertaking such investment becomes much less risky if one or more major long-term customers can be signed up beforehand. In many parts of the world with gas resources but no distribution network, the ideal initial customers may be power stations. A single high-capacity line to a power station is easier, quicker, cheaper and less risky to build than a full-scale distribution network without guaranteed customers. Once the initial bulk-delivery infrastructure is in place, the option to extend the gas network to other customers becomes much more feasible. How such arrangements might evolve in a liberal context is, however, not easy to foresee. A number of major projects linking gas and electricity developments this way are already in progress, notably in Latin America and in Asia, involving consortia of major international companies. All these projects are risky, some more so than others. Some governments are the guarantors of the risk; others may be the source of the risk. The projects will be closely watched, not least by international financiers.

Some electricity networks have recently endeavoured to take advantage of their existing physical infrastructure by adding telecommunications technology to the network, for instance by stringing fibre-optic cables alongside high-voltage transmission lines. In the 1990s, the purported synergy between electricity and telecoms networks has yet to be convincingly demonstrated. In the UK, for example, the National Grid Company has thus far sustained significant financial losses from its Energis venture into telecoms; but its prospects appear to be improving. In the longer term, as indicated earlier, the growing importance of information technology for the electricity network itself may prove to be a potent stimulus for the anticipated synergy with telecoms. As electricity business evolves into electricity services business, this synergy appears bound to intensify, as Working Paper 5 will discuss.

## 4. Networks and electricity technology

The network makes central-station generation feasible. Throughout the history of central-station electricity systems, the attributes of the network have evolved in response to the attributes of the generators. Larger output from a single generator requires higher network capacity, with all that this entails in cables, towers, transformers, switchgear, controls and protective devices. Multiple generators compound the complexity of the network, and impose yet more stringent demands on it. Conversely, to be sure, limitations of network technology, such as the problem of corona discharge from high-voltage AC transmission lines, with accompanying line losses, have historically constrained extremes of central-station generation, quite apart from limits on the generating technology itself. Nevertheless the common technical model of synchronized AC, as described in earlier Working Papers, has eventually encompassed systems including individual generating units with output of up to some 1400 megawatts, and transmission lines operating at up to 700 kilovolts AC.

Having attained such concentrations of interacting generation and network technology, electricity systems have since begun to evolve in the other direction, away from these extremes of concentration, as previous Working Papers have described. Once again, the evolution of the network is likely to track the evolution of the generating technology on the system. In the process, existing network facilities may fare better than existing generators. Large-scale generators whose output becomes more expensive than newer, smaller units may simply be shut down; but large-scale network facilities, such as high-capacity transmission lines and switchyards, established during the phase of maximum concentration of the centralized system, are likely to remain available and in operation. Distribution networks in cities, often now facing capacity limits, may indeed be candidates for upgrading. One option may be superconducting cable, already being demonstrated, able to carry much higher current through existing underground conduits. New generating units, although smaller than their precursors, will probably continue for some time to be connected mainly to the high-voltage sections of the network. Some new generators, however - particularly those built for on-site generation and cogeneration, and decentralized renewables technologies - may be connected to lower-voltage sections, possibly at distribution level rather than transmission level. This will gradually change the proportional roles of the high-voltage and lower-voltage sections of the network, even without some of the more dramatic decentralizing changes anticipated in Working Paper 3.

In a liberal context, when generators and network may belong to different owners, decisions about generating technology - type, size, location and so on - made by one owner may have to be coordinated with decisions about corresponding network technology by a different owner, both presumably under the eye of the regulator and the central controller of the system. Conflicts are bound to arise. Even on existing synchronized AC systems, controversies are already surfacing about generating technologies small enough and clean enough to be sited close to users as so-called ‘embedded generation’, connected to the network at voltages lower than transmission voltage. This generation delivers electricity to local users through the distribution network without recourse to the transmission network. The controversy is not about the technologies for embedded generation, which are still part of the synchronized AC system and function accordingly, but about who should receive credit - and payment - for the benefits they contribute to the system.

In systems now being liberalized, charges for use of the network are imposed in various more or less arbitrary ways. In England and Wales, for instance, each regional electricity company (REC), which owns the low-voltage distribution network in its area, pays the National Grid Company a so-called ‘Transmission Use of System’ (TUoS) charge based on the three distinct half-hour periods of maximum load the REC places on the high-voltage system over a given time. Embedded generation delivering electricity directly into the distribution network during these periods reduces the maximum load on the transmission system, and thus reduces the TUoS charge the REC has to pay, leaving it extra revenue. Many small generators, including a number using renewable energy technologies, insist that they, not the RECs, should receive the credit for reducing the load on the transmission system. The sums involved are not trivial, especially for the small independent generators who operate much of the embedded generation. Some generators argue that receiving payment for this benefit would already make some small-scale renewable generation more or less commercially competitive without subsidy.

Interactions between generators and network in a liberal context will clearly have a significant effect on the choice of generating technology. In due course it may also have at least as dramatic an effect on network technology. The long-standing symbiosis between large-scale central-station generators and a large-scale synchronized AC network is still taken for granted as the basis for forward planning, even in contexts in process of liberalization. However, as earlier Working Papers have argued, this presumption may come under increasing strain. To be sure, the very existence of the requisite large-scale and amply redundant synchronized AC network facilities will sustain the presumption for a time. In any case, significant alteration of the role and nature of the network will require not only investment but major policy changes. Moreover anyone wanting to initiate alterations to long-standing premises about the network may also have to assume unfamiliar risks. Even so, evidence is already visible of changes that may proliferate.

As has been the case historically, initiatives for change in the network originate with generators wanting to use the network in different ways. In the 1990s, however, in a liberal context, the generators may not own the network, and vice versa. The process of change is therefore likely to be explicit, attempting to reconcile the different agendas of different owners. A generating unit may, for instance, be built on an industrial site, primarily to supply the site itself. It will nevertheless probably want a network connection that functions in two directions, to sell surplus output to the network when price and circumstances are favourable, and to take electricity from the network if the on-site generating unit is out of service. If the site capacity is large enough and the connection synchronized, network access will be subject to the central controller of the system, and prices and charges established accordingly. However, the on-site generator is much less constrained by network considerations, and may indeed operate more or less independently of the network for much of the time, especially if the on-site unit cogenerates process steam or heat as its primary output.

If an increasing proportion of generation on a system becomes on-site generation of this kind, the classical role of the network will gradually change. From being essentially a one-way delivery system from central-station generators to users, the network will become a medium of exchange between participants who may be both generators and users according to immediate and rapidly changing circumstances. Maintaining the stability of a synchronized AC system operating in this two-way mode will be a challenge of a different order, especially if at the same time the authority of the central controller is diminishing. In such a context perhaps the most essential technical innovation for the network will be dramatically increased reliance on information technology, providing real-time two-way information about the status and behaviour of the network, including all significant nodes and interconnections, and incorporating some form of automated control of network traffic and access to the network for all potential participants. This will undoubtedly be controversial. Even real-time or half-hour metering for users is already a source of conflict, because of the cost of the devices. The cost of the necessary information technology will certainly come down with economies of manufacturing in quantity; but someone will have to pay. As yet the mechanisms for deciding on and financing alterations to networks in a liberal context remain fuzzy and obscure, as different participants jockey to avoid costs and risks.

One conclusion, however, appears almost unavoidable. Smaller-scale generation, with more and more of it on the sites of users, will lead over time to gradual break-up of the large-scale centrally-controlled synchronized AC system, into a looser configuration of interlinked networks. Some of the attributes of such a configuration are already to be seen, for instance in the existing DC links between separate synchronized AC systems. DC links, and the power electronics that now make them straightforward, may well become much more common, in a variety of applications, for several reasons. A DC link can transfer energy between systems, and provide voltage support, without the need to operate the systems under a single central control. A DC link, moreover, acts as a barrier to block so-called 'transients', unexpected pulses and surges of power and other disturbances that travel all too freely over a synchronized network - a potentially valuable role as AC system margins dwindle.

High-capacity long-distance DC links are now being introduced between separate systems in Europe, notably between Scandinavia and countries to the south. How these links will fit into a more liberal context for system operation as yet remains to be seen; but their comparative ease of operation is likely to make them robust against many of the changes now envisaged as a consequence of the EU Directive opening the cross-border electricity market. A number of other DC links have been proposed, some on a gigantic scale bridging several whole countries. They, however, may fall foul of financing problems against the background of advancing liberalization.

DC may also help to alleviate the problem of expanding long-distance transmission capacity in the face of environmental opposition. Obtaining permission for new transmission lines grows steadily more difficult. Where an AC line exists, however, its capacity can be doubled or nearly tripled by converting it to high-voltage DC (HVDC) operation, at comparatively modest cost, using most of the same hardware. Wherever this option is adopted it will loosen the integration of the network along that particular interconnection.

At the opposite end of the scale of size, small local DC links, power electronics that convert AC to DC and immediately back to AC, offer protection against the vagaries of the large-scale synchronized AC system, and the disturbances that can spread so swiftly and so widely from even a minor malfunction. In OECD countries, users with sensitive equipment such as data banks and other electronics now routinely incorporate electronic 'clean-up' technology at the point where their local wiring meets the external AC network, to prevent so-called 'spikes' and other potentially damaging short-term fluctuations from reaching their equipment. Many users also routinely install emergency on-site generators to provide electricity in the event of loss of power from the external AC network. Over time, a logical evolution of such arrangements may be complete local networks, generating electricity on site for use on site, downgrading the role of the external AC network to that of backup.

In such cases a further evolution seems increasingly plausible. Some small-scale modular on-site generation, including fuel cells, photovoltaics and batteries, produce DC directly. At the same time, a substantial proportion of on-site loads in modern industrial society, including all electronics - computers, telecommunications, and so on - actually require DC, and many others can operate as well on DC as on AC. This suggests the possibility of local networks actually based on DC rather than AC - almost certainly simpler and cheaper than AC, and offering a substantial measure of local control, especially with developments in information technology. Such DC network systems are already emerging as the preferred choice for village-scale electrification in rural areas of emerging countries. In due course they may also come to play a significant role even in urban industrial areas.

One obvious corollary of local networks, whether AC or DC or indeed mixed, will be a drive to maximize the performance of all the technology involved in the network, in whole-system terms. The local network will be delivering services, not just electricity, to all its local users. It will be sold, installed, operated and maintained accordingly, as Working Paper 5 on *Business Futures* will discuss.

**5. Networks and electricity institutions**

The need for a network was a key reason for the distinctive institutional structure of classical electricity systems. The network had to extend through public space, necessitating some form of official permission above and beyond the usual framework of company and commercial law, regardless of who owned the system. In due course, the attributes of the network prompted and justified the establishment of the monopoly franchise for electricity systems, with far-reaching implications for financing and choosing technologies, as earlier Working Papers have described. The monopoly franchise in turn necessitated some form of regulatory oversight backed by government, directly or indirectly. Throughout most of the first century of central-station electricity, therefore, the institutional structure of electricity systems around the world was shaped by the demands of the network. Planning, financing, constructing, operating, maintaining, modifying and extending the network all required decision-making and implementation, within appropriate institutional contexts to define and assign the relevant responsibilities.

As indicated in earlier Working Papers, different systems evolved remarkably different sets of institutions to fulfil these obligations. But one underlying presumption was common to all. The role of the network was to deliver electricity in the form of synchronized AC from central-station generators to decentralized users. The whole institutional context of any particular system - legal status, ownership, management, financial arrangements, regulation and so on - was intended to support the role of the network as a one-way delivery system. A corollary of this role was that the network, operating as a carrier of synchronized AC, aggregated both generation and loads, and eliminated any direct link between a particular generator and a particular user. The one-way nature of interactions through the network was underlined by the crucial function of the central controller, reacting moment by moment to the independent activities of users, directing the system response to keep network operation stable.

Until the 1990s, prevailing institutional arrangements generally considered the network effectively as an extension of the generators, to deliver their output to users. In such circumstances, access to the network obeys simple groundrules. Users connect and disconnect at will, provided only that they are authorized to do so, by some agreement to pay, and that their equipment complies with the basic technical protocols. Generators connect, disconnect and operate under the direction of the central controller, in response to the users. In a liberal context, however, these simple groundrules for network access no longer apply. On the contrary, where liberalization is in progress, terms and conditions for network access appear likely to be increasingly controversial, an institutional issue whose outcome is as yet far from apparent.

Where networks already exist, and systems are being liberalized, network access already follows a variety of different rules. The 'Pool' in England and Wales and 'Nordpool' in Scandinavia employ quite different criteria to determine which generators, and which users, get access to the network over a given time, and on what financial terms. In California, whose ambitious proposals for liberalization are being scrutinized all over the US and farther afield, network access is to be determined by an 'independent system operator' (ISO) and a 'Power Exchange'. As this is written, however, the freedom of the ISO already appears limited, with reports indicating that the inflexible fossil-fuelled generators already in place are to be allowed to operate continuously, effectively at base load, without reference to their competitive status relative to other would-be generators or their contractual ties to users. In a collision between technical imperatives and philosophical desiderata, the technical imperatives clearly carry the day. In the litigious US, the institutional framework for liberal competitive electricity, and the requisite ground rules for network access, will have to withstand a barrage of legal challenges whose resolution will undoubtedly be protracted, costly and messy.

Apart from the fundamental issue of network access, the network dimension also raises other institutional issues for systems being liberalized. For existing systems, if the network is no longer owned or controlled by the generators, who is to decide on system expansion, and who is to pay for it, on what basis? The issue also has implications for network access, when capacity constraint limits the flows between certain nodes on the system. Various mechanisms have been proposed; to date none has really been tested in practice.

An issue both institutional and financial is that of locational value on the network. Should users at the extremes of the network pay more than those close to generators, to reflect the extra cost of the network to reach them? Within monopoly franchise systems, historical convention and political considerations have usually led to a 'postage stamp' tariff structure: all users in a particular category pay the same unit price for delivered electricity, regardless of whether they are densely-packed urban users or thinly-dispersed rural users. This arrangement, amounting to a cross-subsidy, may be a reflection of political realities that give rural voters disproportionate influence on governments; or it may represent an attempt to rectify the perceived disadvantage of living outside cities. Whichever interpretation is chosen, the consequent failure to acknowledge locational values on the network distorts comparative assessment of technical alternatives. In particular, it biases decision-making between generating options.

If tariffs incorporate the true cost of delivering the electricity to particular users, a generator that can be sited close to users has an advantage over a remote generator that incurs higher delivery cost. Yet most analyses of the cost of electricity from different generating technologies simply ignore the cost of delivery, comparing only the cost of units of electricity at the output of the generator. To the extent that this approach remains accepted, it demonstrates an institutional failure to recognize the changing role of the network, no longer simply aggregating all generation and all loads but acting as a much more discriminating intermediary between them. Until the relevant decision-making procedures change, considering the network as a ‘postage-stamp’ delivery service will hamper its evolution into a more flexible and versatile agency. It will also hamper the evolution of generation away from traditional remote-sited large-scale central stations, towards smaller-scale generation close to users.

Any decision affecting such a fundamental policy issue will have to come ultimately from government. No regulator is likely to initiate such a change, nor be willing to take the political consequences. In any case, regulators of systems being liberalized are already facing more than enough immediate problems. In the late 1990s, as a deluge of analysis and comment demonstrates, liberalization is rendering time-honoured regulatory processes and procedures obsolete. Alternatives appear ad hoc and arbitrary. Those who benefit from changes in the electricity system will take the benefits for granted. Those who do not will blame the regulator. For some time to come, the institutional roles and responsibilities of regulators appear likely to be hotly contentious, whatever they do. As electricity business becomes more like other economic and commercial activity in society, some of these tensions may ease, as Working Paper 5 will discuss. But as long as electricity systems need networks, networks will need regulators. Almost by definition, a regulator cannot satisfy everyone. Controversy comes with the territory. Whatever else changes, that will not.

## 6. Networks, electricity and environment

The most obtrusive environmental impact of central-station electricity is the presence of network facilities, especially towers and transmission lines. The impact, to be sure, is primarily visual, unlike the impacts produced by central stations themselves. Nevertheless proposals for transmission wayleaves have long provoked outspoken opposition in many places. In the UK, for example, transmission lines drew vociferous objections in the 1950s, at a time when generating stations could be constructed almost without question. The issue was a quintessential manifestation of the NIMBY approach - ‘Not In My Back Yard’. Objectors accepted that the transmission line must be built, but wanted it somewhere else - inevitably, in someone else’s back yard. As central stations became larger and more remote, transmission lines had to traverse areas of open country, a technological intrusion into what objectors saw as a rural idyll. Similar controversies sprang up elsewhere. In the 1990s, in many OECD countries, getting permission to lay a new transmission line is likely to be more difficult than getting permission to build a new generating station.

The strength of these objections to transmission lines may seem initially disproportionate. They may, however, draw some of their force from the perception that someone else is getting the benefits of the transmission line while the objector gets only the disbenefit of visual intrusion. A transmission line is a vivid instance of this kind of inequity, indeed an almost pure instance; unlike a road or indeed a power station, a transmission line offers no possible benefit of convenience or jobs to compensate for the disbenefit. A power station can be sited at a location so remote that very few people live in its vicinity or can actually see it. But a transmission line may traverse tens or hundreds of kilometres, if not more, and must eventually reach a concentration of loads, usually an urban area. In the 1990s, where there are people there are objectors. Even those who may be indifferent to, say, acid rain or climate change may nevertheless take offence at a series of transmission towers crossing the skyline.

One remedy, often demanded by objectors, is to bury transmission lines. This option is certainly technically feasible; but it may be ten times as costly. As noted earlier, expanding the capacity of an existing transmission line by converting it to HVDC operation may be an alternative, at least for lines adequately long to warrant conversion. But where no line already exists, establishing one may be difficult if not impossible in many places. The apparently superficial environmental obstacle of visual intrusion could yet prove to be a major factor in favour of smaller-scale generation, closer to users and not dependent on long-distance high-voltage transmission.

One other environmental corollary of high-voltage AC networks must also be mentioned. For some years arguments have raged about the possible health effects associated with exposure to the electromagnetic fields surrounding AC cables. A number of epidemiological studies have endeavoured to establish whether such health effects can be measured. The epidemiology of low-level long-term effects is notoriously subtle and complex; to date no study has produced convincing evidence of measurable effects. For the moment, all that can be said with confidence is that if health effects of electromagnetic fields in due course prove measurable, society will be confronted with a daunting problem. The entire planet is now bathed in electromagnetic fields from human activities; synchronized AC will not be the only suspect.

## 7. Network electricity futures

Any electrical circuit more complicated than an electric torch implies a network. Unless the generator and the load are the same size, with the generator dedicated to the load, the interconnection between generation and loads will be a network. The network can be compact and self-contained - think of a personal stereo or a laptop computer. At the opposite extreme is a large-scale central-station synchronized AC system. Working Paper 1 suggested two possible alternative directions of longer-term evolution for the world's electricity systems, and indicated the conditions under which each might evolve. The traditional model, based on large-scale generating units including hydro, coal-fired and nuclear, long-distance high-voltage transmission, synchronized AC and the monopoly franchise, will be able to survive and continue wherever governments can maintain tight central control over system planning, finance and operation - if they can. On the other hand, where governments promote or at least allow liberalization and internationalization, the traditional model will come under increasing pressure, and is unlikely to survive for very long. Earlier Working Papers explored the reasons for this conclusion, and some of its implications.

As this trend develops, it will affect network configurations at least as much as generation, albeit perhaps more gradually. As noted earlier, network facilities are less likely than generating facilities to become surplus to requirements. Truly redundant generating capacity has little if any role to play; if it is unlikely to be dispatched at all, keeping it in operable condition will be expensive, and unremunerative in a liberal context. Redundant network capacity, on the other hand, offers extra system security at comparatively low operating cost, and is unlikely to be retired until the end of its working life - depending on the operating circumstances of the network, including ownership, dispatching and network access arrangements. Certainly no existing wayleave is likely to be abandoned unless and until the entire network configuration has changed beyond recognition.

That said, however, liberalization has already begun to change the operating configuration of existing networks. As earlier Working Papers have noted, an increasing proportion of new generation is in smaller-scale units that can be and are connected not to the high-voltage transmission network but to the low-voltage distribution network, close to users. Some smaller-scale generation is actually on the site of use; and this arrangement may become much more common. Earlier sections of this paper have suggested some possible developments of these trends, including de-integration of large-scale synchronized AC systems, local networks, DC links, and DC operation. Such a configuration will entail very different patterns and structures of control, away from central control to potentially very decentralized control, facilitated by the spectacular expansion of the role of information technology.

Over time, the consequences of these interacting developments may be to change electricity networks from one-way delivery routes into an electricity analogue of the Internet. Such networks will carry real-time two-way flows not just of electricity but of information, between decentralized participants who may interact individually or in groups, bilaterally or multilaterally. The interactions will be mediated by information and system technologies that keep track of who is doing what, for whose benefit and at what cost, with no central control whatever. To be sure, in the 1990s such a configuration and mode of operation for an electricity network appears an outlandish idea. In the 1960s, so did the internet.