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Transforming Electricity: Working Paper 3

Electricity: Decentralized Futures

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1. Introduction: the decentralized dimension

In French a power station is a 'centrale'. A number of other European languages have the equivalent etymology. In the twentieth century the whole conception of an electricity system has been based on the idea of generating the electricity in a 'centrale' or central station. The characteristic that makes a generating unit 'central' is that its output is too large to be used on the site, and must therefore be delivered from this centre outwards, to an appropriate number of users constituting an appropriate load, distributed over what may be a significant area around the central station. The earliest systems were laid out exactly like this, with one large generator and many small loads. The generator might not be geographically the centre of the system; but even for a system whose generator was on a remote periphery, such as a hydroelectricity system, the generator was the centre of all system operations.

An electricity generator converts a less convenient form of energy into a more convenient form. A central-station generator can be located near the less convenient energy, for instance at a waterfall or mine-mouth, in which case the electricity must be delivered some distance to users; or it can be located near the users, in which case the less convenient energy must itself be delivered to the station, for instance as coal by rail.. Either way the station is a centre at which energy arrives in concentrated form, to be converted and sent out from this centre to users. The very concentration of the energy may be one of its most inconvenient features; converting it to electricity allows it to be more easily subdivided and distributed. Paradoxical though this may sound, centralized generation requires decentralized users, and a network linking the centralized parts of the system to the decentralized parts. The more centralized the generation, that is, the higher the output from a given station, the more decentralized the users are likely to be - more numerous and more widely distributed.

A central-station system, even one whose generation is all in large units, therefore already has one important decentralized dimension - the loads on the system. Moreover, essentially for historical reasons dating back to Edison and his contemporaries, these loads are assumed to behave independently of any central control, being connected and disconnected at will by their decentralized owners and users. The rest of the system, the centralized generation and the delivery network, has to respond accordingly. As earlier Working Papers have argued, in a synchronized AC system the actions of the decentralized users in aggregate have to be matched by an overall system response directed by a single central controller, to which all the generation and network components are subordinate, to keep the system stable. The dynamic tension between the centralized and decentralized aspects of the system is inherent in the technical model of the central-station sychronized AC system, and in the institutional and organizational framework in which decisions are taken to keep the system stable.

As the earlier Working Papers have noted, central-station generation arose because of the substantial economies of scale for generators driven by steam power and water power. All the subsequent ramifications of synchronized AC systems stemmed from this single fact, reinforced by the possibility of combining this economy of scale with a comparably large-scale concentration of inconvenient energy such as a waterfall or - from the 1950s onwards - a coal mine, refinery or nuclear reactor. Linking separate central stations together, and unifying their networks under a single controller, removed the final constraint on scale. Synchronized AC systems have expanded steadily ever since; so have concentrations of load connected to them, especially urban concentrations of load served by highly concentrated central generation often well outside the urban area.

Systems have evolved almost organically, continuously rather than discontinuously, guided ultimately by the central controller. The pattern of evolution has always been fundamentally determined by the attributes and requirements of what is there already, the need to maintain stability while modifying and enlarging the system. Throughout the twentieth century, even apart from the massive destruction caused by wars, most of human society's built infrastructure has evolved in discontinuous steps. Existing buildings have been torn down and replaced, roads torn up, relaid and widened, and so on, with no necessary relationship between what is happening in one neighbourhood and in another. Even gas networks have been removed and replaced, as natural gas has supplanted town gas. But the evolution of synchronized AC systems has always been constrained by the need to keep the lights on throughout the process of change. Within a single synchronized AC system all change has ultimately been directed and controlled from the centre, on an essentially continuous and uninterrupted basis. Historically, in exchange for the cheap electricity delivered by the economies of scale available from concentrated steam and water power, decentralized users have delegated responsibility for electricity and control over it to the central authority. As a corollary, they have also come to assume and expect that the central authority - ultimately the government - is responsible for keeping the lights on.

Earlier Working Papers have suggested that, over the longer term, liberalization and internationalization of electricity systems - where they occur - may make such arrangements difficult if not impossible to sustain. This should not, however, be construed as a fatal drawback of liberalization and internationalization. Unlike systems to deliver fuels, which necessarily entail carrying a physical commodity from its source to the point of use, systems to deliver electricity can be configured in many different ways. In principle, electricity can be generated and used anywhere, at a price. System configurations to date have been determined by the interaction between technical options, economic priorities, institutional arrangements and the attributes of the existing system -

all now changing at unprecedented speed in many parts of the world. The longer-term implications of the changes demand urgent investigation; but they may not be detrimental, and may indeed be beneficial, especially if they are clearly understood at an early stage, and policies formulated accordingly.

Liberalization and internationalization will inevitably diminish the role of the central authority, at least as it has been exercised in traditional franchised monopoly systems within national borders. This Working Paper will examine the implications of reducing the role of the 'centre' for an electricity system - of 'decentralizing' the system. 'Decentralizing' is an ungainly and frankly ugly term, but accurate. It describes the process of change from a configuration in which both physical and institutional power are concentrated, to one in which both are more dispersed. This Working Paper will compare significant aspects of 'centralized' and 'decentralized' systems, the reasons for change from one configuration towards the other where it may occur, and possible longer-term implications.

2. Electricity and centres

The common technical model of electricity systems worldwide has something of a paradox at its heart. Generating electricity in ever larger central stations has in turn required ever more far-flung and dispersed users, to take up the output of the large stations. Linking the central stations to the dispersed, 'decentralized' users has entailed eventually vast delivery networks. Originally individual centres, each with its own circle of users, stations were then linked under joint control, to use generating capacity more effectively and provide backup for outages. Then they were connected into a high-voltage grid, effectively eliminating any direct link from a given centre to a given user. Earlier Working Papers described how in a synchronized AC system stations, networks and users' loads all operate in real time as a single machine under a central controller. The central controller directs the response to the activities of individual users as they connect and disconnect their loads. The decentralized users then depend on the central controller to keep the lights on, not only from moment to moment but over time.

The presumption in the public mind of some central responsibility to keep the lights on is a relatively recent development, established only after the Second World War. In the industrial countries that eventually formed the OECD, electricity systems were recognized as a crucial constituent of national economies. Governments assumed direct or indirect responsibility for franchised monopoly systems; and the public came to take this central responsibility for granted. An electricity system was a 'utility', a public service provided under the aegis of government. In countries with communist regimes, and in newly-independent developing countries, electricity systems were unambiguously a branch of government; the central responsibility to keep the lights on was a corollary and consequence of government monopoly, not vice versa. In the 1990s, wherever central-station synchronized AC electricity systems operate, this presumption of central responsibility to keep the lights on still generally prevails. However, as Working Papers 1 and 2 have argued, recent developments are undermining the presumption. Over time it may become untenable. It may also become unnecessary.

Central-station generation and the central control structures associated with synchronized AC networks have a profound effect on finances, institutions and technology choices. Centres are concentrations of power - physical, financial and institutional. Such concentrations offer various economies, not only of physical scale but also of transaction and other institutional costs, to the ultimate benefit of users, at least in principle. Nevertheless a traditional franchised monopoly system represents an extreme form of centralization and concentration of power, as the status of its users indicates. Users are nominally 'independent', but only in the narrowest instantaneous sense. They can connect to and disconnect from the system at will and independently; but otherwise they are captive. They have no other say in system operation or management. Needless to say they have to use equipment acceptable to the system. The bills arrive willy-nilly, users have to pay what the system charges or face being denied access to it, and users ultimately bear all the risks. In recent decades, on many supposedly mature systems, failures of central decision-making, leading to ill-judged investment, inadequate system performance and unwelcome side-effects, have increased tensions between the system centre and its dispersed captive users, compelled to accept the risks and and pay for the consequences of such failures. In many transition and emerging countries, users want electricity but cannot reliably obtain it; governments maintain centrally controlled monopoly systems which are nevertheless unable to deliver what their captive customers want. Liberalization has been represented as a way to reduce such tensions. One key way in which it does so is to reduce the power of the centre, in favour of increasing the power of users and other less central decision-makers. The longer-term consequences of this shift of power may be dramatic.

In the short term, moment by moment, the centres of decision-making on a traditional electricity system are the users and the central controller, who determine collectively how the system operates in real time. In the longer term, the system structure itself evolves and changes, necessitating more far-reaching decisions - for instance to build new generating plant, to finance it, to grant the requisite permits for siting, water use and other environmental impacts, to fuel it and to operate it. On a synchronized AC system, each addition to the system also has to be compatible with what is there already, an implicit or explicit responsibility of the central controller. If the system is a traditional franchised monopoly, the longer-term decisions are made in centres of responsibility that may also include:

- government at various levels, particularly national, establishing the legal, fiscal and environmental framework, and appointing and overseeing the regulator;
- system management, either as a branch of government or as an entity under the aegis of government;
- the regulator, responsible for setting tariffs and other financial frameworks;

- entrepreneurs participating on the system, as owner-operators of existing facilities, or as prospective owner-operators of additional facilities;
- investors and financial organizations providing backing for system management and entrepreneurs;
- fuel suppliers; and
- equipment manufacturers for all parts of the system including users.

As liberalization reduces the power of central authority, how may this array of decision-making centres evolve, under financial, technical, institutional and environmental pressures? Which centres will become more powerful, which less, why and with what effects? Will electricity systems evolve to include more centres, each less important, with less proportional influence on the whole system? Or will they perhaps evolve towards even fewer centres, in the form of extensive portfolios of assets perhaps internationally owned, but with less day-to-day involvement in operations? A wide range of possibilities exists. The central controller of a synchronized AC system, historically the most important decision-making centre of all, may come to face an especially acute challenge. In some contexts the balance of advantage may continue to favour overall central control, with the entire system subject as before to the overriding power of the central controller, and concomitant allocation of responsibilities and risk. On the other hand, in a liberal context, shifting patterns and distribution of responsibilities and risk may gradually loosen the integration of the system, with links of a different kind between formerly synchronously integrated parts of the original system. The traditional central power may gradually disperse more widely. If those with the responsibilities also bear the risk, and if those bearing the risk accept the responsibilities, systems formerly centralized may gradually decentralize.

3. Decentralization and electricity finance

Early electricity systems were financially very risky ventures. They were usually funded either by governments - that is, by taxpayers - initially at the local level, or by risk capital from private financiers willing to speculate. Either sort of system could rapidly lose its backers a great deal of money. Systems were small, numerous and thinly populated with users willing to buy electricity. Competition was fierce both between different electricity entrepreneurs and between electricity, town gas and direct fuel use. With the passage of time the public in many parts of the world gradually came to recognize that electricity was worth having and worth paying for, not merely as an ostentatious novelty but as a genuine improvement in the quality of life. In any given locality, however, financial arrangements for any electricity system remained more or less precarious until the concept of the monopoly franchise became accepted, and in due course established in law.

The monopoly franchise provided a central anchor for the future finances of the system. The increasingly heavy capital investment required for generating plant and network could now be undertaken with some confidence that it would be recovered and indeed provide a return. Elimination of competition from alternative suppliers of electricity tied the local populace to the franchise holder over the requisite period of time. As electricity became increasingly desirable, the revenue from captive customers throughout the franchise area flowed in to the franchise holder at the centre, in a reassuringly steady and usually swelling stream. The combined effect of the monopoly franchise and the growing desire for electricity transformed electricity systems from financially risky speculation into stable long-term low-risk investments suitable for widows and orphans.

A monopoly franchise was usually subject to some form of official overview or regulator, to prevent abuse of monopoly power; but electricity systems effectively became cost-plus activities, with tariffs and charges set accordingly, at least in those countries that eventually formed the OECD. The local electricity system came into the category of 'public service', a local 'utility', with unique responsibilities to serve customers who no longer even recognized themselves as 'captive'. An electricity system with central generating stations and a network was not only a monopoly in law but a 'natural monopoly', or so it seemed, able to exercise central power over its users and its finances. Nevertheless, despite classical economic strictures about the drawbacks of monopolies, monopoly franchise electricity systems worked fine. Systems expanded steadily, technology advanced, electricity prices fell, electricity use grew. The whole arrangement including finances met with general approval and satisfaction. Each system had its central controller, its central planning and its central finance. Few even noticed that the central authority exercised the responsibility for electricity but the users bore the risk, including the financial risk. In OECD countries most people came to take the arrangement for granted. Even in the 1990s, after more than a decade of upheaval affecting electricity systems, most people still do.

Central stations and the other physical facilities they necessitate represent a major concentration of capital assets. Their owners, whether governments or private investors, expect appropriately concentrated returns. This has obvious implications for the charges imposed on the decentralized users of the system, from which the system derives its revenue. In a traditional monopoly franchise system, the central authority determines the financial requirements of the system, to recover operating costs and a return on capital assets. The monopoly ensures that these requirements are met, both immediately and over the longer term. Captive customers must pay the tariffs stipulated centrally or be denied access to the system, with no recourse to any alternative except to generate their own electricity in isolation - historically an expensive and inconvenient alternative, without the economy of scale of central-station generation, quite apart from the problem of outages of on-site generation with no backup.

In a franchised monopoly system the central authority has powerful financial leverage, sometimes ruthlessly exercised. It has ready access to capital in very large sums on very generous terms, because of the essentially guaranteed revenue stream from its captive customers paying for an essential service, quite apart from the government guarantees often also available to it. It is therefore able to make centralized investments on a grand scale. Throughout the 1950s and into the 1960s, as electricity use expanded rapidly, building ever larger generating units, often grouped on the same site for administrative convenience, made obvious sense. Large increments of capacity were welcome; unit capital costs came down and fuel efficiency went up. The logic appeared impeccable; but it had its limits. From the late 1960s onwards, the central authorities of many electricity systems undertook major investments that were to prove ill-advised and costly. Their forecasts of electricity use and of plant construction schedules and costs diverged ever farther from reality, a problem exacerbated by the long lead times of very large units. When challenged, however, the central authorities loftily insisted that they knew best how to meet the needs of electricity users. Even when errors of judgment became impossible to ignore, sometimes with price tags in billions, the central authorities rarely acknowledged any fault. Nor did they bear the consequent financial burden. Captive customers and taxpayers did. Many complained bitterly, but they ultimately paid up. They had no choice. But their discontent helped to trigger the upheaval of the 1990s. The central authorities of many electricity systems overreached themselves, arrogating to themselves so much central decision-making power, with so little answerability for their failures, that they antagonized their customers, the public and the politicians. When innovative electricity policies emerged, proposing radical redistribution of decision-making power away from the old centre of the system, the central authorities of some systems found that they had few allies left to defend them. Many people welcomed the onset of liberalization of electricity systems precisely because it reduced the power of the centre - not least the unilateral financial power.

Earlier Working Papers have alluded to one immediate corollary of liberalization where it has occurred: the shift away from central stations based on very large coal-fired and nuclear units, towards more moderate-sized stations based on modular gas-fired combined-cycle gas turbine units. A key reason for the shift is of course financial, as earlier Working Papers described: lower capital cost, more rapid generation of revenue, more rapid amortization and so on, as previously rehearsed, indeed a whole new framework of timescales and discount rates. But the shift to smaller modular generating units also reinforces the trend toward reduced centralization, technical, financial and institutional: smaller units but more of them, more widely distributed both physically and financially. Wider, more decentralized ownership of the capital assets on the system introduces a different spectrum of decision-making and requires different institutional arrangements, no longer directed unilaterally from a single powerful centre, as will be discussed below. The financial flows, too, are more multifarious and decentralized, rather than converging inevitably to the centre. To be sure, decentralization of decision-making may entail increased transaction costs. But more equitable distribution of responsibilities and risks between participants on the system may well warrant paying a premium in additional transaction costs.

In a liberalized context, the available finance and its criteria for risk and reward are substantially different from those in a traditional centrally-managed system. These different criteria exert a strong influence on the size and distribution of relevant centres, both physical centres such as generating units and decision-making centres such as owners and operators. In a liberal framework, financial criteria create pressure for smaller centres and more of them - pressure to decentralize. At the same time they create opportunities for financial intermediaries, who can reduce transaction costs for less powerful participants by aggregating small decentralized transactions of various kinds, for instance into portfolios of contracts, as Working Paper 5 will explore. On the other hand, financial criteria and risk allocation in a liberalized context may also, of course, stimulate mergers, acquisitions and alliances, to hedge risk and assemble more balanced portfolios of assets. Such re-integration may reconfigure institutional and market power into new concentrations with new centres, possibly international. This may pose a challenge to governments trying to foster market forces, to minimize monopolies and to control oligopolies.

Even in a fully liberalized context, with genuine competition for all participants, governments themselves will of course continue to play a key role in electricity finance, albeit less explicitly than has hitherto been common. Decentralization will change the way governments deal with electricity systems. They will still have to oversee monopoly networks (Working Paper 4) and define tax structures and commercial law for companies and contracts (Working Paper 5); they may accept responsibility to provide electricity services to the poor; and they may also take measures to tighten environmental controls on electricity activities, with financial as well as other implications. Decentralization, however, will compel governments to keep track of many more participants, for every aspect of electricity from company accounts to emission controls. As electricity systems decentralize, governments may come to view them not as a unique and distinctive focus of central responsibility but as an economic sector not different in kind from any other sector of industrial manufacture and marketing, subject to the same sort of tax regime and legal framework as any other economic activity in the society.

Most of the foregoing applies in particular to electricity systems undergoing at least a degree of liberalization and accompanying decentralization - primarily those in OECD countries. In transition countries, the process of reducing the power of the centre, that is, the old central planning of the communist era, applies not only to electricity but to the entire economy, as democratic structures supplant authoritarian ones. The metaphor, however, is inevitably suggestive. A traditional electricity system, a monopoly centrally managed and centrally planned, fits very well into an centralized authoritarian structure like the old communist regimes, as Lenin memorably remarked. The financial structure can be, as it invariably was under communism, utterly opaque, concocted by central decrees, subsidies, smoke and mirrors. For countries in the throes of transition from communism to democracy, making government finances intelligible and coherent has been and remains a serious challenge, with electricity systems prominent in the process. Some transition countries have begun to liberalize their electricity systems, to attract foreign investors and up-to-date technology. The interaction between emerging democracy and electricity liberalization in transition countries may gradually decentralize both political authority and electricity systems in parallel.

In some emerging countries a similar process may arise, albeit for rather different reasons. Some emerging countries with more or less authoritarian governments regard their electricity systems as a manifestation of central power, and are reluctant to surrender any measure of control. But a number of such countries have economies growing at spectacular rates, eager for expanded access to electricity. Despite government desire to retain central control, the need to add system capacity, most readily by involving foreign companies, foreign capital and imported techology, may force such governments to loosen their central grip on the system. If decentralization of power delivers more satisfactory electricity services, even authoritarian governments may find the process difficult to contain. The political corollaries may be interesting.

An accompanying development, already modestly in evidence, is the change in approach of international funding organizations to electricity projects in emerging countries. For decades the World Bank and other agencies have focused on financing mega-projects, notably large central-station generating plant, both fossil-fuelled and hydroelectric. Among the arguments in support of this stance has been the insistence that the administrative cost and complexity of smaller, more decentralized projects would be disproportionate and unmanageable. In the late 1990s, nevertheless, stung by intense international criticism of its historical record, the World Bank appears to be shifting its policy focus away from financing mega-projects to financing and participating in smaller, more numerous and more diverse undertakings, more in tune with local social and environmental circumstances. If this approach continues it will further reinforce the trend of decentralization, both directly and through the concomitant influence on client governments. The Bank's experience may also give useful guidance to other financial bodies as they attempt to manage not large-scale central electricity projects but decentralized programmes and portfolios, without incurring unacceptable administrative and transaction costs.

4. Decentralization and electricity technology

Traditional generating technologies based on water power and steam power exhibit - at least in principle - major economies of scale in unit sizes up to 1000 megawatts or more. These technologies are therefore inherently central, especially in the sizes ordered from the 1960s onwards. For a steam-powered unit on such a scale the requirements for land and cooling water and the output of low-temperature heat are all far too large to accommodate conveniently even on the largest heavy industrial sites. Such units are in fact almost always remotely sited, linked directly to high-voltage transmission lines, as of course are water-powered units installed in large dams. These large units in turn necessitate a vast infrastructure of delivery networks, transformers, switchgear, protective devices and so on, integrated into a large-scale synchronized AC system, all operating under ultimately central control, to maintain system stability.

The elaborate infrastructures of the world's many synchronized AC systems were almost all set up under monopoly conditions. (Among OECD countries, only Finland has two separate networks covering the same territory.) Such a network can be characterized as a natural monopoly; in fact the monopoly has been almost invariably not only 'natural' but conveniently recognized as such in law, by government grant of an exclusive franchise to a single central authority to generate, deliver and sell electricity within the franchise area. The captive customers of the monopoly pay not only for the generation of the electricity they use, including capital, fuel and operating costs, but also for the establishment, operation and maintenance of the vast delivery network that the central stations require.

In a monopoly context, however, the final cost to customers is entirely aggregated in a single unit tariff, centrally imposed. They receive little if any information about how much they are paying for the separate constituents of the system. Indeed, because of internal cross-subsidies and the inevitably arbitrary valuation of the many different assets of different scales, ages and service lives, the cost attributable to the separate components in an integrated monopoly electricity system is essentially indeterminate. Statements, for instance, about the comparative costs of different generating technologies, considered as additions to an existing synchronized AC system and stated as the cost of a unit of electricity, should always be regarded as suspect. The interaction between the existing system and the proposed new generation may alter the cost structure of the entire system. This is especially true if the new generation deviates significantly in attributes from those of classical central-station generation by steam or water power. The technological inertia of an existing electricity system is due in some measure to the presumption that proposed changes to the system must be assessed, financially and otherwise, according to the criteria that created the existing technical configuration.

Earlier Working Papers have noted the expanding range of generating technologies now coming into play, starting with the gas turbine, which have scale attributes quite different from those of traditional steam and water power. One consequence of this difference is that these new technologies, economic in smaller unit sizes, are a sharp break with the centralizing tendency of traditional technologies. Adding smaller, modular generating units, and more of them, to an existing system swings the trend away from centralization towards decentralization. Even when assessed according to the criteria of the traditional central-station system, gas-turbine combined-cycle stations now frequently emerge as the best option for adding new generation. But their advent is also changing the criteria to be applied henceforth.

Another determinant of the traditional central-station configuration, as noted earlier, has been the availability of concentrated but inconvenient energy, in waterfalls, coal mines and latterly refineries and nuclear reactors. Generation based on the gas turbine, however, uses energy that is already convenient and flexible, whose concentration can be adjusted to suit - natural gas delivered continuously to the generator, in whatever quantity is desired, large or small. Gas-turbine generation undermines key traditional reasons for large-scale remote central-station generation. Furthermore, because gas-turbine stations can be not only adequately small but also adequately clean and quiet, they can be sited much closer to users, and indeed on the site of use. The option of cogeneration of electricity and heat becomes increasing attractive, offering not only much higher fuel efficiency but direct control of site electricity supply, including its reliability and its quality, a consideration that will figure ever more prominently. A system that formerly delivered electricity from remote central-station generators to decentralized users can thus evolve into a system in which not only the users but also the generators become decentralized.

Gas-turbine generation fosters this new trend. Other technical options, likewise cited in earlier Working Papers, may drive it further and faster. Generation not merely close to users but actually on site may soon utilize not only gas turbines and diesels but also fuel cells, renewable energy technologies and on-site high-efficiency energy storage with batteries or flywheels. These technologies are inherently decentralized, available in sizes that match on-site loads, benefitting from economies of mass manufacture rather than unit scale, and amenable to easy maintenance and replacement. They are nevertheless routinely discounted as still 'uneconomic'. The argument is already tendentious, and will become more so. It assumes without question that each new unit of generating technology has to be assessed according to how well it can be adapted to the existing central-station synchronized AC system. The assessment is based on the criteria that created the existing centralized system over its long continuous evolution. These criteria, however, are unable to assign appropriate economic and operating advantages to technologies that are inherently decentralized. As a result the criteria can be used, intentionally or unintentionally, to disparage technical options that do not conform to - and indeed may threaten - the classical system configuration.

This threat is nevertheless growing. The classical configuration of central-station generation brings with it the whole panoply of synchronized AC, its networks, controls and central controller. Emerging technical options, with generation at a smaller scale and closer to users, can still of course be based on centralized synchronized AC; but the reason why is less obvious, except as a consequence of the massive inertia of the existing technical and institutional infrastructure. This inertia cannot be underestimated; but it should be recognized as inertia first and foremost, rather than as a positive counter-argument against decentralization. Technology moves on. The limited range of options for economic generation of electricity determined the technical configuration of the classical system; but the range of options is now steadily widening, and will bring inexorable pressures to bear on the classical central-station system. The growth of on-site generation and cogeneration, and the emergence of 'embedded generation' connected to local networks, are further evidence of the decentralizing tendencies promoted by new technical options. They in turn are supported and sustained by a rapidly expanding array of new system control technologies, and by power electronics that enable easy interconnection between AC and DC networks. Information technology will play a key role in managing decentralized systems, their operations and their finances; and IT capability is expanding exponentially, month by month. In at least some contexts, decentralization of generation ranging from large industrial sites through smaller to airports and rail stations, shopping malls, office buildings, hotels, hospitals, schools and potentially even individual residences is no longer inconceivable. The implications of such potential evolution are profound. To take but one obvious example, in any context where liberalization may lead to major decentralization of systems - for instance much of the OECD, wherever natural gas is readily available - the investment status of some high-voltage long-distance AC transmission lines may become seriously risky.

Research and technology development for technical options suited to decentralization continues to accelerate - often backed by international consortia whose support clearly indicates expectation of early commercial success. Fuel cells now come very prominently into this category; and full commercialization of fuel cells alone would wrench previously centralized electricity systems into an entirely new world. Even more dramatic, if less immediately in prospect, would be the impact of fully competitive photovoltaics. Incorporated into the fabric of buildings and operating the equipment inside, photovoltaic tiles and panels might no longer even be considered as 'electricity generators', but simply as part of the system that provides the illumination, the electronics and so on, as other parts of the building fabric provide shelter and comfort. Metering the photovoltaics might become no more relevant than metering the daylight. The status of technologies like these cannot be adequately evaluated according to criteria drawn from classical central-station systems. All too often such inherently decentralized technologies find themselves 'playing away', on the home terrain of the centralized system and according to its rules. What the new electricity technologies need, and what they may trigger, is a complete 'paradigm shift', in which the classical concept of an electricity system gives way to a twenty-first century alternative. Unlike the evolution of electricity systems over the past century, the transition to full decentralization, where it happens, may be neither continuous nor gradual. Those who are unprepared may be left with stranded assets on a crippling scale.

5. Decentralization and electricity institutions

Working Papers 1 and 2 discussed the evolving relationship between governments and electricity systems, in the context of internationalization and liberalization. Historically, governments have been the ultimate centre of power over electricity systems, often directly, sometimes indirectly; as noted earlier, the presumption has been that governments are ultimately responsible for keeping the lights on. The institutional arrangements to plan, operate and manage electricity systems - ownership, organizational and financial structures and status, interactions with government, and so on - vary widely from system to system. But all have been predicated on the common technical configuration of central-station generation of synchronized AC in a monopoly franchise area. The earlier Working Papers considered some implications of moves to internationalize and liberalize electricity systems, including institutional implications. This paper has suggested the further corollary that an electricity system subject to these changes may gradually decentralize. If so, the changes will affect not only the physical but also the institutional configuration of the system. A decentralized institutional framework for electricity will differ profoundly from the centralized institutional frameworks that guide decision-making for classical electricity systems.

Governments instigate the process of change, and the initial decisions are taken centrally. As noted in the earlier Working Papers, governments are by no means all eager to alter the status of electricity systems under their jurisdiction. In many countries electricity systems are a practical manifestation of political power, and their governments wish to retain this power centrally for political reasons. Some will undoubtedly succeed in doing so, at least for some considerable time to come; Working Paper 1 postulated the example of China. Others, for various reasons, will not; consider, for but a single vivid example, the ferment already bubbling up in India. State Electricity Boards facing a financial abyss are being forced into restructuring and possibly even privatization; independent power producers led by foreign companies are gaining a strong and expanding foothold in many state systems, while insisting on more realistic prices for electricity; and major Indian industries, fed up with power cuts and poor quality electricity from the state systems, are ordering their own on-site generating plant. The central authority of Indian state governments over their electricity systems is now under severe pressure; and tensions between state governments and India's national government further aggravate the conflicts.

The Indian example is only one of many similar situations in the late 1990s. Governments facing this now-familiar combination of circumstances may be compelled to relax their previous central control of decision-making for electricity - control over planning, permitting, investing, purchasing, hiring and operating - even though the relaxation of central control runs directly counter to their political instincts. The alternative may be increasingly frequent and comprehensive collapses, extending over entire systems, like the system collapse in December 1996 that left 145 million Indians in two northern states without electricity. Central control is not a political asset if it leaves 145 million constituents in the dark.

The institutional framework of an electricity system identifies the responsibilities for decisions. Even if the ultimate authority lies at the centre, a hierarchy of less important decision-making extends out from it. Relaxing the central control enhances the importance of other decision-makers on the system - in effect, begins a process of decentralizing the decision-making. Restructuring an electricity system away from the classical centralized model means reassigning responsibilities for decisions and empowering new centres of authority. It also reallocates risks, financial and otherwise. In the classical centralized monopoly model, the decentralized users ultimately bear the risks of mistakes by the central authority - the cost of ill-judged investment, superfluous employment and incompetent operation. In the centralized system the risk, paradoxically, is more or less completely decentralized. In a more liberal decentralized framework, conversely, risks can be allocated to specific and identifiable decision-makers; and mistaken decisions may recoil directly on those who make them. In this way, oddly enough, decentralizing the institutional structure makes the risks less diffuse, and more recognizably central.

Earlier Working Papers have discussed the overriding importance of the central controller of a synchronized AC system for short-term operational decisions, particularly dispatching, noting however that a liberalized context may lead to reduced redundancy and system margins. Unlike the physical configuration of a synchronized AC system, the institutional framework of the system can change abruptly and discontinuously without threatening system stability, provided the change does not threaten the ultimate decision-making authority of the central controller. Generation, transmission, distribution and supply can be institutionally unbundled and decentralized into separate activities linked by explicit contracts and accounts. A power station, a network, indeed an entire system can change owners more or less instantly, at the stroke of a pen, reassigning decision-making responsibilities to the new owners. The legal and statutory responsibility of an owner can change by government edict at a given moment, as can the fiscal status. Even the role of a given owner on a system can change with a decision, for instance by a regulator or central controller, as long as the regulator or central controller retains the authority to make and enforce the decision.

As systems decentralize, this situation may change. On a classical central-station system most generation is in units very large compared to most loads. Decisions affecting generation are therefore more important for system stability than those affecting loads, and institutional responsibilities are arranged accordingly. Generating units above a certain capacity, perhaps 1 per cent of the total, can be connected and operated only under explicit direction of the central controller. Most loads, by contrast, are substantially less than 1 per cent of the total, and are connected and operated with no reference to the central controller. However, if unhappy with the charge imposed unilaterally, the user's only sanction is to disconnect. An owner-generator delivering electricity to the network - that is, an IPP - is in a similar position. If unhappy with arrangements such as dispatching, payment or access to the network, the owner-generator's only sanction is to disconnect.

As the proportion of decentralized smaller-scale generation on a system rises, this institutional arrangement will come under mounting pressure. Even in areas with monopoly franchise systems, users have mostly been free to generate their own electricity, so long as they do not want to connect to the network. The deterrent has been the cost, and the problem of outages of on-site generation. Liberalizing the institutional framework reduces obstacles to on-site generation and enhances its advantages, creating opportunities for technical and commercial innovation. On-site generation, by reuniting generation and use, restores control to the user and brings together risk and responsibility, decentralizing not only the technical configuration but also the institutional framework. On-site generation becomes a significant centre for decision-making, not only for its user but also - if it has a connection to the network, for backup, or even to sell surplus electricity output - for the system as a whole. Both site operator and network operator can break the connection to the network, under some agreed institutional arrangement. If the on-site generation is cogeneration, the link to the site load rather than the network becomes even more predominant, with heat probably the primary output and electricity secondary.

Change in this direction will pose problems. Decentralizing decision-making, moving it closer to users, will weaken the authority of the 'centre', including that of the central controller. As system stability becomes more precarious, users will become more concerned to acquire adequate control over the quality and reliability of the electricity reaching their loads, reinforcing the trend toward on-site generation and further weakening the centre. This is turn will alter the role of the network, and the institutional framework in which it functions; Working Paper 4 will examine the implications.

At the same time, a quite different institutional trend is already evident and appears likely to accelerate. Under liberalization, as ownership and enhanced decision-making capability devolves away from the centre to decentralized sites and system components, a new type of ownership has also emerged - portfolio ownership, including both foreign and international holdings of sites and facilities not merely on a single system but on many different ones under different governments and indeed in different countries, creating supranational centres for decision-making that may affect several different systems at once. Reducing the power of the centre of a classical electricity system thus means not only 'decentralizing' institutional power toward dispersed decision-making centres. Some institutional power may actually be further concentrated, into supranational centres of ownership, decision-making and control. Mergers and acquisitions both within national borders and internationally are creating ever-larger and more powerful electricity organizations, fundamentally different in structure and outlook from classical single-system organizations within their isolated fiefdoms. These new electricity organizations encompass not only affiliates and subsidiaries of electricity system owners, but also plant manufacturers, fuel suppliers, private finance and other interested parties. They are already redefining and enlarging the scope of their business interests and activities; Working Paper 5 will explore possible future developments.

6. Decentralization, electricity and environment

Central-station electricity systems were one of the prime stimulants of the NIMBY - Not In My Back Yard - approach to environmental impact. A coal mine has to be where the coal is, and similarly with other extractive industries. But a central generating station can have a choice of sites, and a transmission line an even wider choice of wayleaves. Many early environmental objections to electricity facilities did not therefore argue that a facility should not be built - only that it should not be built 'in my back yard'. 'Put it somewhere else' - presumably in someone else's back yard. As central stations became ever larger and more remote, more and more people enjoyed the benefits, at the expense of the unfortunate and powerless few in the vicinity of the stations, usually in rural areas, who suffered worse and worse local environmental impacts. Large steam-power stations produced visual intrusion, noise, disturbance, land degradation, waste and spoil and often air and water pollution. Large hydroelectric stations could be even worse, flooding land and submerging settlements completely.

This environmental inequity is an inherent corollary of a central-station electricity system - advantage for the decentralized many at the cost of concentrated disadvantage for the few. It has often been exacerbated by the central role of government, as advocate for a proposed electricity project while at the same time purporting to adjudicate on its suitability in some form of planning inquiry. Those who object to a proposed installation must put their case with their own limited resources, while those who propose the installation can draw on the resources - including finances, access to information and political leverage - not only of the system itself but often of the government that backs it. From the 1960s onwards many unequal battles were fought, in both OECD and non-OECD countries, over large-scale central generating stations. The great majority were duly given the go-ahead.

In the 1970s, however, some environmental objectors to new electricity facilities adopted a new approach. NIMBY arguments pitted one group of objectors against another, each accepting that a facility must be built, but wanting it built somewhere else. These decentralized, dispersed objectors were thus susceptible to the 'divide-and-rule' tactic of the central planners. The new approach drew decentralized objectors together into a more concentrated coalition, presenting a united front of opposition not merely to the proposed location of an electricity facility but to the very idea of the facility itself. The main focus of this new approach was the proposed rapid build-up of nuclear power stations, not only in many OECD countries but also outside the OECD. Whatever the merits or otherwise of the arguments adduced for and against nuclear power, it called forth an array of opponents, initially local, then national and indeed international. The nuclear opposition, however, never became concentrated in any single centre, remaining an informal and decentralized network both within individual national borders and internationally. The interests of this network also gradually expanded, to address other environmental aspects of electricity, to share information and analyses, and sometimes to cooperate on particular issues. In the 1990s essentially every environmental aspect of electricity attracts not only local but national and international attention, sometimes combined with opposition, from a wide range of more or less decentralized non-governmental organizations, whose experience and expertise is often comparable to that of electricity organizations themselves. The environmental implications of electricity are now under observation as never before, and will remain so. In recognition of this fact many electricity organizations now submit their activities to environmental assessment, and publish the results. As systems are liberalized they have to satisfy not only central authorities but also the general public, as decentralized users begin to realize that they need no longer passively accept whatever the central system deigns to deliver. Working Paper 5 will discuss the business implications of customer choice, including the marketing of more environmentally acceptable 'green electricity'.

As noted earlier, one of the key reasons for the central-station configuration of electricity systems has been the availability of concentrated sources of inconvenient energy, in particular large hydro and coal. Using them has obvious advantages, but causes environmental impacts that are similarly concentrated. Earlier Working Papers argued that liberalization of a system will reduce the role of large hydro and coal for financial reasons. Decentralization may also do so for other reasons, including environmental. Large hydro, by definition, cannot be used for decentralized generation. Coal is awkward and expensive to transport to and store at decentralized locations. Moreover, customers given the option to choose their sources of electricity, and the requisite information about the sources, may choose sources with lower environmental impact, as Working Paper 5 will discuss. This tendency will be reinforced if new generation is built closer to users. In such circumstances users will receive both the benefits and the disbenefits of any form of generation, including environmental impact, and indeed will have more explicit involvement in the policies that guide the choice of options.

For this and other reasons, local environmental impacts are likely to be lower in a decentralized context. But decentralized generation means more sources of impact, possibly in due course a great many more. That may make cumulative global impacts, particularly carbon dioxide emissions, more difficult to address, as long as local generation continues to use fossil fuels, presumably primarily natural gas. A decentralized context means more and smaller participants. Standards may be set centrally, but emissions will be harder to monitor and standards harder to enforce. International environmental agreements between central governments may lack credibility if no plausible mechanisms can guarantee their implementation. In that event, establishing tradeable emission permits or joint implementation of climate change mitigation measures will face even more daunting difficulties. Electricity systems that become decentralized may present environmental problems more akin to those of transport systems, and accordingly more challenging.

7. Decentralized electricity futures

In the late 1990s some electricity analysts have begun using the term 'distributed', as in 'distributed resources', 'distributed utilities' and similar expressions. The term 'distributed', however, is not really strong enough to characterize the full import of what could happen to electricity systems over the longer term. The essential meaning is 'more uniformly distributed': less 'lumpy' in space, time, money, and control - that is, less centralized. In the nature of the technology, an electricity system that is less centralized is also less hierarchical. It has not just one single controller at the centre, but many dispersed across the system. As a consequence, the nature of the 'system' changes, technically and institutionally. The linkages and controls within the system are multi-directional rather than from the centre. The structure becomes more like that of the Internet, linked to local area networks of computers. Controls employ distributed processing; information flows in both directions over a multiplicity of pathways. The role of the network thus also changes dramatically. Instead of being the heart of a single synchronized AC machine, the network becomes a looser array of many local electricity networks, linked by AC or DC as appropriate. Working Paper 4 on *Network Futures* will examine the implications.

The process of decentralization will be neither inevitable nor trouble-free. Issues raised by liberalization may also impede decentralization. Large centralized assets that may become stranded in a liberal competitive framework will not be lightly surrendered, as events in the US are already demonstrating. Even those governments that are comfortable with less central control over electricity systems may face political controversy about some possible consequences. What, for instance, becomes of a traditional concern such as 'security of supply' in a liberal and decentralized framework? Uniform tariffs set centrally often mean implicit cross-subsidies that benefit smaller users, rural areas and the poor. What, if anything, will take the place of these cross-subsidies, and the social welfare they provide? Such issues are politically sensitive and potentially explosive. Decentralization will not be straightforward, nor painless.

Where it does occur, the process will probably follow a different sequence of stages in the existing, essentially mature central-station electricity systems of most OECD countries compared to that in the fast-changing systems in emerging countries. In OECD countries on-site generation and cogeneration will slowly increase, initially at the largest industrial load centres, then at progressively smaller industrial, commercial and public-service loads. Many load centres, especially those concentrated in conurbations, may be less readily amenable to decentralized generation, even with on-site delivery of natural gas. Entrepreneurs may see business opportunities in improving the performance of buildings and other end-use equipment as an adjunct to decentralization, to make local loads smaller and more stable, better suited to local generation; Working Paper 5 will explore the possibilities.

In certain areas of OECD countries - islands, mountainous regions and other localities costly to connect to the central system - and in many non-OECD countries in which existing systems are hard-pressed to satisfy demand, the process of decentralization may follow a somewhat different course. Establishing local generation and a local network may be cheaper, easier and faster than extending the central-station network to remote areas of modest load. The rural areas of many developing and emerging countries are unlikely ever to see the arrival of classical synchronized AC transmission lines. Decentralized local systems, including those using local resources of renewable energy such as wind, solar and biomass, appear much more feasible. They also lend themselves to local management and local control, highly desirable as a way to reinforce the political stability of rural areas and reduce the population pressure on congested megacities. To be sure, how such local developments may interact with the authoritarian central governments of some emerging countries remains to be seen.

As central-station systems gradual decentralize, the process may look superficially like retracing the early history of electricity in reverse. Generation will move back closer to users, with local networks under local control - systems at first glance much like those of the late nineteenth century. But the differences will also be profound. Using innovative technologies for generation, for electricity use, for information and for system management and control, decentralized electricity systems will belong not to the nineteenth century but to the twenty-first.