A services model of the electricity industry with particular attention to network services

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Summary

This paper discusses a service model for the electricity industry, considering generators, network elements and end-use equipment. The central tenet of a services model is that the task of the electricity industry is to deliver end-use energy services, such as illumination, computing services and space conditioning. The paper focuses on the role of network services within a services context and discusses the extent to which network services might be made contestable through competition between network service and distributed resource providers. The paper concludes that enhanced end-user participation in ancillary service, spot market energy and derivative trading is a prerequisite to enhanced network service contestability. This is necessary to overcome the ambiguity that presently exists over legal liability for unsatisfactory delivery of end-use energy services, which in turn is a primary driver for investment by network service providers. A second prerequisite is accurate measurement of interval energy, supply availability and supply quality for every network user. This is because supply availability and quality are most network-dependent for small end-users.

The complex physical behaviour of the electricity industry requires sophisticated trading arrangements that allow all industry participants, small and large, to make commercial decisions about operation and investment as well as availability and quality of supply. To facilitate efficient decision making, the "obligation to supply" should be replaced by standardised spot and forward contracts, and "energy service facilitators" should be appointed to assist small end-users to make energy service decisions that are both economically efficient and environmentally sound. The present role of retailers should be allowed to atrophy. End-use equipment should be designed to be robust to poor availability and quality of supply and to permit end-users to participate in the provision of voltage, frequency and availability-related ancillary services.

There appear to be two possible commercial frameworks for embedded generators and small end-users:

- *A retail market for each zone substation with support from competitive energy service facilitators, or*
- *A franchise monopoly distributor-retailer for each distribution zone, charged with facilitating least-cost energy services for small end-users within that zone and regulated accordingly.*

In the first approach, enhanced retail electricity markets would first be introduced and then merged over time with wholesale markets into a single network-wide nodal market framework in which all generators and end-users participated. This approach would have to overcome challenging technical and political barriers to deliver efficient outcomes. In the second approach, the nodal market would be implemented for the meshed transmission network only, and a franchise distributor-retailer would implement a managed retail market within each distribution zone under regulatory oversight. The latter approach may be more practical in the near term and may remain the preferred approach in the long term, particularly in rural areas where network effects are most important and effective retail competition seems least plausible.

It is too early to say whether network services can be made fully contestable because only time will tell whether efficient nodal spot and derivative markets can be established even at the transmission level. In the meantime, network services will continue to be provided by an uncomfortable mix of regulated and unregulated network service providers in competition with distributed resource providers.

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Services provided by the electricity industry

Overview

An electricity industry can be defined to be an interconnected set of generators, network elements and end-use equipment that has the purpose of delivering end-use energy services. Electrical energy is an intermediate energy form that exists only for a fleeting moment in a network, because it travels at the speed of light and there are no cost-effective means of storing it. Thus the electricity industry operates by a continuous process of converting primary energy forms into electrical energy in power stations, with a continuous flow of electrical energy through transmission and distribution networks to end-use (or storage) equipment, in which electrical energy is continuously converted into end-use (or storage) energy forms.

The basic building blocks of an electricity industry are generators, network elements and items of end-use equipment. These building blocks interact in a tightly coupled, mutually dependent manner. Electrical energy can only flow if there is at least one generator of electrical energy ready to produce electricity from primary energy forms, which is joined by at least one conducting path (one or more network elements in series) to at least one item of end-use equipment that is ready to convert electrical energy into an end-use energy form. A generator can only operate correctly if there is sufficient demand for electrical energy to continuously absorb its output, and an item of end-use equipment (without end-use storage) can only operate correctly if it receives the continuous flow of electrical energy that it requires to operate. Network elements provide the connections between generators and loads required to support the energy flow.

Thus the electricity industry can be described as operating in a “just-in-time” manner to provide a continuous flow of energy services rather than a set of discrete products. Just-in-time relationships in other industries are commercial arrangements between small numbers of firms within an industry and are designed to enhance the competitive advantage of participating firms. However in the electricity industry, the just-in-time relationship results from laws of physics rather than commercial contracts. It is unavoidable and it involves all industry participants, including small end-users. The electricity network provides the physical means by which the just-in-time relationship is implemented in real-time. Automatic control schemes and coordinated decision-making processes (including commercial decision making) are used to keep the physical just-in-time relationship stable and to organise future industry activities.

Due to its physical properties, the electricity industry has unusually short-term coordination requirements. Because of capital intensity, long installation times and long asset lives, it also has unusually long-term coordination requirements. The interactions between industry participants are complex, due to the shared nature of the electricity network and the dependencies between all items of electrical equipment in an electricity industry. Finally, unlike in most other industries, end-users and end-use equipment participate directly in the just-in-time relationship due to its physical basis, exercising a crucial influence on both short-term and long-term behaviour of the industry, and thus on industry design. For this reason, arrangements to coordinate the decision making of generators, end-users, network service providers and power system operators take on particular importance in the electricity industry. Moreover, unlike in most other industries, there is no intermediate physical role for a retailer. Instead, end-use facilitators should be introduced to address the wide disparity in size ($> 10^6$) and sophistication of industry participants.

Forward contracting and effective communication between participating firms are essential parts of any just-in-time relationship. In the electricity industry, forward contracting and effective communication should involve all industry participants, including small end-users. Direct end-user participation is required to manage the real-time flow of electricity through the network because of the lack of intermediate storage, and to facilitate efficient investment decisions.

The traditional electricity supply industry had an implied forward contract with end-users, known as the “obligation to supply”, which provided an open-ended guarantee to meet all of an end-user’s present and future electricity requirements in return for a simple (typically energy-only) tariff. The open-ended nature of the obligation to supply was justified on the grounds that electricity was an “essential service” (particularly for residential end-users), which governments were obliged to provide, usually via a regulated monopoly supply industry. However the legal entitlements of end-users were unclear, because an open-ended guarantee was physically impossible to meet and the introduction of high consumption discretionary “lifestyle” end-uses undermined the concept of an essential service for residential end-users.

An important motivation for electricity industry restructuring was to move responsibility for future electricity requirements from governments to end-users. To complete this transition, the traditional obligation to supply should be replaced by spot and forward contracts for all end-users that have specified forward volume-price combinations (which could be determined by profiling techniques). Variations would then be traded at spot prices and end-use facilitators would assist end-users to manage this process. Two commercial contracts would be required: - one between end-user and distribution network service provider for local network services related to availability and quality of supply (tradeable transmission-market access rights and local network-related ancillary services), the other between end-user and market operator for energy and global ancillary services (including global network issues). Meters would record key indicators of quality and availability as well as spot market interval energy.

This transition is proving politically difficult to manage, particularly with respect to small end-users. It would be facilitated by the introduction of a new category of industry participant, an energy service facilitator that assisted small end-users to make appropriate decisions. This role could be competitive but an alternative would be to retain regulated franchise monopoly distributor-retailers and re-direct them towards facilitating least-cost energy services for small end-users. Both approaches would require regulatory oversight.

Availability and quality of supply

The ability to accept or deliver energy flow (injection or off-take) at a particular point of connection to a network is measured by the term “availability of supply”. Likewise, the parameters that determine the “quality” of electrical energy flow at a particular point of connection to a network are referred to as “quality of supply”. Both availability and quality of supply can change instantaneously and vary from one node to another in a network.

For a three-phase AC network, the ideal quality of supply is defined as a set of three phase sinusoidal voltage waveforms of rated frequency, rated voltage and balanced phase relationship (a number of different rated voltages may be used in transmission and distribution networks).

Imperfections in quality are measured by deviations from the ideal, particularly by deviations in voltage magnitude and frequency, waveform distortions and imbalance between phases.

All items of electrical equipment are designed to tolerate some imperfections in quality of supply. However, outside its design tolerance, electrical equipment may malfunction or suffer damage, and thus cause deteriorations in the provision of energy services, even if energy is still flowing through the power system. Thus the value of the end-use energy services depends not only on the flow of electrical energy, but also on its availability and quality (for example, "black-outs" and "lamp flicker" represent inadequate availability and quality respectively)[1].

Power system operators continuously monitor and manage power system security (by reducing risks to future availability of supply) and quality of supply in the main transmission network. Traditionally, power system operators have paid less attention to availability and quality at end-users' points of connection than in the main network. Instead, aggregated measures of distribution network performance have been relied on. However this will have to change as formal commercial contracts with end-users replace the informal obligation to supply. This is because end-users are interested in their own outcomes, not those for an average end-user.

Short-term deteriorations in availability or quality can be important to end-users as well as prolonged deteriorations, and metering at the points of connection of all generators and end-users should record key indicators of availability and quality of supply as well as the flow of energy. Electronic meters could be readily designed to record such information.

Ancillary services

Power system operators use ancillary services to maintain supply quality and availability within acceptable bounds. Because they must operate rapidly, ancillary services are often automatically controlled. Because power system operators manage ancillary services centrally, their decisions can pre-empt market-based decision-making. Therefore ancillary service arrangements should be designed jointly with energy spot and derivative markets, which can only deal with electrical energy flows averaged over time and space and generally assume that the energy flow at any point in the network meets a quality specification.

Ancillary services can be classified as frequency-related, voltage-related, security-related and restorative:

- Frequency-related ancillary services are used to maintain short-term supply-demand balance on a system-wide basis (except where the frequency in a subsystem is decoupled from the frequency in the remainder of the system by a DC link – as would apply to Basslink).
- Voltage-related ancillary services are used to maintain voltage magnitudes within an acceptable range. Their influence on voltage is primary local rather than system-wide, however they do influence total network losses.
- Security-related ancillary services aim to reduce the likelihood of involuntary load shedding or poor quality of supply following unexpected disturbances to power system operation. These are typically caused by the failure of one or more generators or network elements, or by unexpectedly high demand that leads to cascading disconnections of network elements

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[1] The quality of energy flow to an item of end-use equipment is a function of both the quality of supply provided by the power system and the parameters of the item of end-use equipment.

and/or generators. Stochastic primary energy resources (eg wind energy) may become an issue if they achieve high levels of penetration and there is insufficient diversity between the stochastic processes.

- Restorative ancillary services are designed to restore power system operation to normal following a major disturbance.

Generators, network elements and items of end-use equipment can all either provide, or trigger a need for, ancillary services. Measurements of energy flows and supply availability and quality, at the points of connection of all generators and end-use equipment, provide an important starting point in identifying causality as well as confirming that an ancillary service had been provided.

Ancillary services must be paid for, raising issues of measurement, causality and willingness to pay and reducing the total industry benefit and possibly the volume of trade. However, if insufficient ancillary services are provided, industry benefit may be reduced due to tighter operating constraints, higher network losses or poor quality and availability of supply.

Services provided by end-use equipment

Items of end-use equipment are location specific. They absorb electrical energy from the network at their point of connection to provide energy services for end-users, and are the primary source of the societal benefit provided by the electricity industry.

Items of end-use equipment can continuously deliver their intended energy services so long as supply available and quality remains within design parameters. However the ability to deliver service can fall rapidly if design parameters are not met.

End-user satisfaction and the economic value of the electricity industry as a whole depend on the value derived from energy services delivered minus the cost associated with delivering those services. The economic value of the electricity industry is also reduced according to the value of services that were forward-contracted[2] but not delivered. Non-delivery of an energy service can be very costly to an end-user, because the valued derived from an end-use energy service often greatly exceeds the cost of the electricity supply needed to deliver it, bearing in mind that the probability of non-delivery is usually both low and difficult to quantify.

Under the traditional "obligation to supply" model, the cost of non-supply can only be estimated, for example by the "Value of Lost Load" used in the National Electricity Code. However it would be better to assess the financial risk of non-delivery for each end-use and specify it in a commercial forward contract. The financial risk can vary greatly between end-uses and between end-users, and can depend on the timing and duration of non-delivery.

Some items of end-use equipment have a wide tolerance to interruptions to supply and/or to poor quality of supply. Examples include storage water heaters that may only require supply for a few hours per day to deliver hot-water services, and portable computers with in-built batteries that are very tolerant to supply interruptions, waveform distortion and a wide range of voltage magnitude and frequency.

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[2] The forward contract might be implicit under an "obligation to serve" or explicit under a commercial contract

However, other items of end-use equipment can be quite sensitive to supply quality and availability, for example many desktop computers. While it is often easy to reduce the sensitivity of such equipment, at present manufacturers see few incentives to do so. This situation would be improved by the introduction of efficient retail markets for small end-users that encompassed ancillary services, spot energy and forward contracts, or by franchising monopoly distributor-retailers with a mandate to deliver least-cost end-use energy services for small end-users.

End-use equipment can provide ancillary services. In fact, power system operators rely on the fact that for most items of end-use equipment, the rate of energy consumption automatically falls as supply voltage falls (a voltage-related ancillary service) and, for many types of motor-driven equipment, the rate of energy consumption automatically falls as supply frequency falls (a frequency-related ancillary service).

It would often be possible to modify end-use equipment to enhance these inherent ancillary services and, by adding low frequency or low voltage disconnection or demand reduction functions, end-use equipment could also provide security-related ancillary services. Such enhancements in equipment design should be encouraged whenever they are cost-effective.

Services provided by generators

Generators are location specific. Their core service is to inject a flow of electrical energy into the network at their point of connection. They may also provide voltage- and frequency-related ancillary services, as well as security- and restoration-related ancillary services. However they may not always see appropriate commercial incentives to do so.

Large generators can be quite sensitive to voltage and frequency excursions, in which case they should become willing purchasers of ancillary services that reduce the risks of such excursions if appropriate markets developed.

Generators have to make decisions with important inter-temporal links, such as unit commitment, fuel purchasing and investment. Thus they usually have a strong interest in forward contracting.

Some generators exploit primary energy resources that are energy flows rather than storable commodities. Examples include run-of-river hydro and wind, wave or solar generators. Such generators are classified as “non-dispatchable” as they can only adjust their output below an upper constraint set by the primary energy flow level, which is typically a stochastic process.

Services provided by networks

Network elements may be divided into a number of categories:

- *Network series elements* provide connectivity between locations – they allow the spatial distribution of generation to differ from the spatial distribution of demand, creating opportunities to capture important societal benefits. The ability to install additional series elements may be restricted by difficulties in obtaining easements.
- *Transformers* are used to link network series elements that operate at different nominal voltages, allowing the nominal voltage level to be chosen to suit a particular task, such as long-distance high voltage transmission carrying large energy flows, versus short-distance

low voltage distribution of small energy flows. Variable ratio transformers also provide voltage control capability.

- *Network connection elements* are used to connect network users, such as generators and end-use equipment, to the network. Connection elements can make a vital contribution to meeting agreed availability and quality of supply at the point of connection. This role should be monitored for commercial purposes by appropriate metering.
- *Network shunt elements* (such as capacitor banks) are used to provide voltage related ancillary services. They may be thought of as specialised generator or end-use equipment.
- *Network protection, switching and control elements* are essential to managing the configuration of a network, during normal operation and under fault conditions. They must be managed in a coordinated way as part of overall power system operation. All switching elements have a rated interruption capacity that cannot be safely exceeded, and which may restrict the total generation (depending on technology) that may be sited in a particular part of the network.
- *The network as a whole* provides the just-in-time sharing mechanism via which all operating generators and all operating end-use equipment interact. In addition, the holistic network provides security services via redundant parallel energy flow paths and by allowing other operating generators to instantaneously substitute for a failed generator.

The ratings of individual network elements create an outer set of constraints on energy flows through a network. Security constraints, set by power system engineers on the basis of engineering judgement, may further restrict the allowed energy flows through a network, creating an inner set of constraints. Security constraints take account of possible future modes of behaviour during normal operation plausible equipment outages that may prejudice availability and/or quality of supply and switchgear interruption capability.

Security constraints are probabilistic in nature and may not map well onto flow constraints on network elements because they typically depend on the characteristics and operating states of generators and loads as well as those of the network itself. As a result, security constraints may be difficult to represent adequately in electricity spot and derivative markets.

Subject to flow constraints, an electricity network operates in a holistic manner, and energy flow through a network is normally determined by path impedances rather than by active control of energy flows. In addition to permitting spatial separation between generation and demand, a network provides an important aggregation function, so that, subject to flow constraints, the set of operating generators connected to a network jointly supplies the set of operating end-use equipment connected to the same network.

The network's physical aggregation function is particularly important in exploiting diversity in the uncertain future behaviour of individual generators and end-use equipment. Thus, assuming that the behaviour of generators and loads can be described as independent stochastic processes, the network's aggregation function greatly reduces the need for individual end-users and generators to tightly coordinate their activities compared to what would be required in a bilateral just-in-time relationship[3]. This aggregation function is more effective at transmission than distribution level.

In the very short term, networks contribute to frequency-related ancillary services by supporting immediate substitutability between generators when one fails, and purpose-designed network elements, such as shunt capacitor banks, provide voltage-related ancillary services. Networks also contribute to security services, as described in the next section of this paper.

In summary, the network's physical aggregation function can be thought of as implementing an obligatory, industry-wide, just-in-time physical contract that efficiently manages the short-term variations between the stochastic supply and demand patterns of individual generators and end-use equipment, subject to flow constraints.

The importance of diversity between stochastic processes in an electricity industry can be understood by considering situations when there is little diversity, such as on summer or winter peak-load days, when the demand of weather-sensitive end-use equipment becomes highly correlated. This has become a primary driver for network investment in the National Electricity Grid, particularly in distribution networks supplying homogeneous sets of end-use equipment, such as residential estates with a high penetration of air-conditioners. Another example of loss of diversity is a type-failure of generation, such as low rainfall across a number of important hydro catchments, simultaneous occurrences of low wind speeds at many wind farms or coincident identical failures of generators of the same design.

The network's aggregation function is of little benefit when there is little diversity between the stochastic processes of generation or demand. Instead, other measures must then be used to manage the just-in-time relationship by efficiently rationing network capacity. These should be organised in an industry-wide manner because of the holistic nature of electricity industry operation. Examples include voluntary demand reduction, uninterruptible supplies and stand-by generation. A key challenge is thus to develop ancillary service, spot and derivative market arrangements that facilitate an efficient network rationing and investment process.

Categorisation of Network Services

The electricity network in a power system can usually be described as consisting of a (high voltage, high power) transmission network, to which are connected a number of discrete (low voltage, low power) distribution networks.

The boundary between transmission and distribution networks is ambiguous. One useful distinction is to define transmission networks as those parts of the total network that are normally operated with a number of parallel energy flow paths ("meshed" network operation), and define distribution networks as those parts of the total network that are normally operated as a set of radial feeders, each with one energy flow path ("radial" feeder operation). One or more radial distribution feeders emanate from a "zone substation", which is the point of connection between the meshed transmission and radial distribution networks. The set of radial distribution feeders emanating from a particular zone substation may be defined as a "local distribution network".

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[3] This is an important reason why a "pool" model of trading is more appropriate for electricity than bilateral trading, and why bilateral trading models always have "balancing markets" that are, in fact, pool-style spot markets.

Energy flows are shared between the parallel paths in a meshed network according to the ratio of path admittances (the inverse ratio of path impedances). However the flow constraints associated with the parallel paths may not share the same ratio as the path admittances. This is one reason why distribution feeders are normally operated radially. Another reason is that protection requirements are simple and cheap for a radially operated feeder that has its only point of supply at the zone substation.

Particularly in urban areas, sectionalising switches are commonly provided in radial distribution networks to allow supply to be restored to most end-users if a section of a distribution feeder is damaged, or to allow the distribution network to be reconfigured as load patterns change. The ability to reconfigure a distribution network also provides considerable flexibility to match uncertain spatial patterns of demand growth within a distribution zone.

There are still ambiguities in labelling meshed network operation as transmission and radial network operation as distribution. For example, a high-voltage interconnector between two regional transmission networks may operate with a single (radial) energy flow path, but still be regarded as part of a transmission network. A radial interconnector shares one important characteristic with radially operated distribution feeders, which is that a fault on the interconnector may disconnect the two regional networks.

When a fault occurs on a network element, network protection, switching and control equipment operates to isolate the faulted element from the rest of the network subject to fault interruption capability. This is done to minimise damage to the faulted element while allowing normal operation to be restored in the remainder of the network to the extent that it is possible to do so.

Isolation of a faulted element in a meshed network allows energy flow to continue on the one or more paths that were in parallel with it, albeit with the possibility of a lower flow constraint. As a result, at least some and possibly all energy services that were being provided by the faulted element can continue to be provided. In the context of a nodal electricity market, a flow constraint would usually be accompanied by a spot price reduction “upstream” and a spot price increase “downstream” of the constraint.

Isolation of a faulted element in a radially operated feeder leads to an immediate interruption to the energy flow that was previously carried by that element. Loss of supply will occur downstream of the fault unless there is sufficient downstream embedded generation to continue operating as an “island”.

Loss of supply is best regarded as a market failure because there is no price that can achieve supply-demand balance. The risk of market failure can be managed by either financial or physical insurance (eg a standby generator or uninterruptible power supply). In either case, the amount that end-users are willing to pay for insurance will depend on their assessment of the risks associated with loss of supply.

A defining characteristic of a “strongly meshed network” is that the failure of any one element does not introduce a binding flow constraint. Failure of an element in a “weakly meshed network" will cause a reduction in energy flow capacity, which may be large enough to be difficult to manage in a market context. Thus weakly meshed networks may exhibit some of the characteristics of radially operated networks.

We can also characterise meshed networks as either well or poorly matched internally and externally with respect to the energy flows they are called on to support.

In a network that is well matched internally, the ratios of the ratings of parallel paths through the network roughly match their admittance ratios, and the available path ratings are well utilised during normal operation. Note that it is unlikely that a meshed network will be well matched both in normal operation and following a contingency when one or more faulty network elements have been disconnected.

In a network that is poorly matched internally, the ratings of some parallel paths through the network do not match their admittance ratios and thus the ratings of some paths cannot be fully utilised. In some cases it may be beneficial to open-circuit a constrained flow path in a meshed network that is poorly matched internally, despite the loss in security of supply that may result.

Poor external matching implies that a network is either significantly under-utilised or, at the other extreme, constrained for at least some common operating conditions due to a mismatch between the ratings of network elements and the ratings of the connected generation or end-use equipment. It is hard to avoid poor external matching with high penetration of correlated end-uses such as air-conditioning.

Services provided by regional transmission networks

A regional transmission network is a somewhat artificial concept that can be defined as a transmission network that mostly behaves as a strongly meshed network. Regional transmission networks provide connectivity over long distances, connecting remote power stations and major load centres in a common regional "pool".

The key services provided by an ideal regional transmission network are to allow the spatial pattern of generation within the region to be largely independent of the spatial pattern of demand; to capture the benefits of diversity in demand and generation within the region; and to provide high availability and quality of supply throughout the regional transmission network. An ideal regional transmission network would allow largely unrestricted competition between the generators connected to it both during normal operation and following network contingencies.

However, the cost of a strong network, constraints on easement acquisition and growth in demand for network services mean that the ideal regional transmission network cannot be realised in practice for any period of time. Typically, the strength of a regional transmission network will vary between strong and weak across the region[4].

Within major urban areas, sub-transmission networks provide interfaces between the main transmission network and the zone substations that feed distribution networks (this distinction may not be so clear in rural areas). Within its geographical reach, an ideal sub-transmission

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[4] See, for example, Transgrid's Annual Planning Statement for 2002.

network would provide the same level of services as an ideal regional transmission network. However, for similar reasons, ideal sub-transmission networks are difficult to realise in practice.

The very largest items of end-use equipment are connected directly to sub-transmission networks at (possibly dedicated) zone substations. However most end-use equipment is connected to the radially operated distribution networks that emanate from zone substations.

In summary, regional transmission networks provide the following services subject to network losses and flow constraints:

- Pooled connectivity between remote generators and large load centres within the region, which captures benefits of diversity through aggregation and provides support for competition between generators in the region.
- Connectivity, through sub-transmission networks, to zone substations.
- Network connectivity for the very largest end-users, such as aluminium smelters or steel mills.
- Frequency, voltage and security-related ancillary services.

Services provided by interconnectors between regional transmission networks

An interconnector between two regional transmission networks can be regarded commercially as providing an arbitrage function between the two associated regional electricity markets. If the interconnector forms part of a network loop, there may be little reason to distinguish it from other parts of the meshed transmission network – the two regional transmission networks effectively become one (possibly weakly connected) combined transmission network. In this case, “interconnector” is a somewhat artificial concept. In the case of a radial interconnector (i.e. one that does not form part of a network loop), disconnection will interrupt energy flow, causing separation of the regional markets at either end.

In summary, interconnectors between regional transmission networks provide the following services subject to flow constraints under normal operation and contingencies:

- Connectivity that supports arbitrage between the regional markets at either end of the interconnector, possibly to the extent of effectively merging the two regional markets into one. Connectivity captures the benefits of diversity (to the extent that it exists) between the regional power systems, and increases the level of competition in the regional markets.
- Frequency, voltage and security-related ancillary services, primarily by exploiting diversity between the market regions. Controlled interconnectors such as DC links may behave differently with respect to ancillary services than AC interconnectors.

Services provided by distribution networks

Most end-use equipment is connected to local distribution networks, which provide connectivity to transmission networks via zone substations. In most cases, there is little or no embedded generation connected to the local distribution network and instead it provides connectivity to remote power stations. In commercial terms this service can be described as transmission-market access.

As the penetration of embedded generation increases, the concept of a “local market” based on a distribution network connected to a zone substation becomes more useful. Also, the technical arguments for radial distribution feeder operation become less compelling and meshed operation becomes more likely to be the preferred option, blurring the boundary between transmission and distribution networks.

The ability to flexibly reconfigure radially operated urban distribution networks permits efficient management of uncertainty in the spatial distribution of demand within each zone. Also, it is usually possible to adjust zone boundaries in urban areas by distribution switching operations, further enhancing the ability of the distribution network to manage spatial uncertainty in demand. There are fewer opportunities to provide spatial flexibility in rural distribution networks.

In summary, radially operated distribution feeders can provide the following services subject to flow constraints:

- Access to the transmission-network based market for all but the largest end-use equipment, subject to faults on radially operated feeders.
- Aggregation that depends on the extent of diversity in feeder load (or generation).
- A local market based on the local distribution network connected to a zone substation, particularly when there is significant embedded generation.
- Flexibility to manage spatial uncertainty in demand in urban areas.
- Voltage-related ancillary services.

Decision making in the electricity industry

Short-term industry operation

Short-term industry operation must be centrally controlled even in a restructured industry, because the rapidity, complexity and industry-wide nature of the decisions that must be taken precludes commercial decision-making, at least for the time being.

Industry operation has three important aspects:

- Forward planning to understand the nature of plausible future operating scenarios and to acquire adequate ancillary service resources to manage future operation in that context.
- Operational decision making to deploy and operate ancillary services to manage operation in the present state and for plausible near-term future operating states.
- Operational decision making to drive the industry towards targets set by commercial models.

The operating context is defined by the operating characteristics, controllability, and configuration of the set of power station, network and end-use equipment that constitutes an electricity industry. Given the appropriate information, industry operators can estimate their ability to manage industry operation in the event of plausible disturbances (contingencies) and thus define the boundaries of a safe operating regime.

Operating constraints may be set for security reasons, or by the level of energy flows that can be tolerated by a particular network element or set of network elements, for example due to thermal limits. In the case of a security constraint, operation at a higher level of energy flow is deemed to be inadvisable because of the risks associated with plausible single or multiple contingencies – usually unexpected failures of items of equipment.

The more redundant paths there are through a network (i.e. the "stronger" the network), the less likely it will be that binding security constraints will be set by contingencies related to failures of network equipment. Similarly, generation contingencies are less likely to set binding security constraints if the industry has a large number of small generators than if it has a small number of large generators.

Because they are systemic rather than device specific, security constraints can usually be relaxed by a number of options involving various industry participants, such as prohibition of network maintenance outages at appropriate times, operational changes in patterns of generator and/or load dispatch, or the specification of generator or load operating levels following a contingency.

Short-term industry operation has commercial implications of the following kinds:

- Industry operators must acquire and use ancillary service resources to manage industry operation, and these resources may involve power station, network and end-use equipment. This may require investment as well as operating expenditure.
- Some items of equipment may be dedicated to providing a particular ancillary service, however many will be capable of providing more than one ancillary service as well as participating in energy transactions. Thus there are likely to be joint product issues that involve overlaps between centralised and decentralised decision making.
- Industry operating constraints reduce industry benefits of trade and costs must usually be incurred to relax them. The costs to relax constraints may be explicit, such as investment in network augmentation, or implicit, such as increasing the risk associated with one or more contingencies.

In summary, short-term industry operation in a restructured electricity industry involves decision-making within a centralised operational framework even if all other decision-making is via a decentralised commercial framework. Short-term industry operation involves both immediate and forward-looking decisions to acquire and deploy appropriate ancillary service resources. It can involve power station, network and end-use equipment.

Decisions that appear to be optimal within the centralised operational framework may conflict with decisions that appear to be optimal within the decentralised commercial framework. This is partly because the centralised operational framework emphasises the total industry perspective while the decentralised commercial framework emphasises the industry participant perspective. It is also partly because the commercial framework can at best convey a simplified model of the electricity industry, while the operational framework must consider the full physical complexity of the industry.

Commercial decision making

Commercial decision-making can be defined as those decisions made by an industry participant that have the primary purpose of maximising the commercial return to the participant.

Commercial decision-making is often categorised as either an operating or investment decision. However, there are overlaps between these categories. An alternative distinction that recognises this overlap is to classify decisions according to whether they have consequences for future decision-making. Decisions with consequences for future decision-making can be described as decisions with inter-temporal links. In the electricity industry, they include unit commitment, maintenance scheduling, fuel stockpile management and all forms of investment. Inter-temporal links range from short-term such as unit ramping and unit commitment, to long term such as the management of multi-year hydro storage and investment in long-lived assets.

Commercial decision-making in a restructured electricity industry occurs within the commercial framework provided by electricity markets, network pricing and planning, and ancillary service arrangements. To achieve an efficient industry outcome, the commercial framework must provide appropriate commercial signals over the forward time horizon necessary to coordinate decisions with inter-temporal links.

In Australia, the wholesale commercial framework is most developed within jurisdictions participating in the National Electricity Market (NEM), and is mainly specified by rules contained in the National Electricity Code (NEC), which cover ancillary services, spot market energy, pre-dispatch and projections of system adequacy, and network pricing and planning.

The NEC also contains rules for conducting “settlement residue auctions” (SRA) for the revenues associated with the notional interconnectors that are represented in the NEM spot market algorithm.

Unfortunately, there are no rules in the NEC for other derivative markets, such as in swaps and options, which are nevertheless essential to support efficient commercial decision-making with intertemporal links. Moreover, at present the retail commercial framework does not replicate the wholesale commercial framework, which seriously reduces the likelihood of achieving efficient industry outcomes through commercial decision making. This is because the commercial signals seen by end-users, network service providers and “embedded’ generators are not consistent with those seen by large generators.

Coordinating decisions by industry participants

The just-in-time nature of the electricity industry means that the short-term operating decisions of all participants should be carefully coordinated to maximise the net benefit of industry operation. Demand-side options should receive equal consideration to supply-side options. Such coordination could be achieved through a combination of equipment design, direct control and price signals for ancillary services, spot energy and derivatives. A prerequisite is accurate metering of supply availability and quality as well as interval energy for all network users.

Examples of the traditional centrally controlled approach to power system operation include centralised unit commitment and automatic generation control (AGC) of a generation portfolio (peak, intermediate and base-load); centrally controlled reactive power resources and off-peak storage water heating; and centrally regulated tie-line flows between regional networks.

In Australia under the NEC, unit commitment decisions are decentralised under a commercial framework and hybrid arrangements are used for dispatch and AGC. The NEM spot market has been largely successful in delivering efficient operation of existing power stations, albeit with some concerns about the exercise of market power. However, end-user participation is restricted by the embryonic nature of retail electricity spot and derivative markets. Recently, markets have been implemented for frequency-related ancillary services, but again, end-user participation is limited apart from the inherent response due to equipment design. Voltage-related ancillary services are still largely implemented in the traditional manner.

The electricity industry is capital intensive with long asset lives. Also, most electrical equipment has limited alternative use and thus low salvage value. Moreover, the industry has important social and environmental externalities. Therefore, careful coordination of investment decisions is required to achieve economically efficient, socially appropriate and environmentally sound outcomes.

The traditional industry was centrally planned on the supply side (generation and network) and often used to implement social and industry policy on the demand side. A key achievement of electricity industry restructuring in Australia has been to replace central generation planning with market-driven decentralised generation investment. However sound investment decision making requires the support of well-functioning derivative markets that provide timing and location signals, and those signals are hard to provide without a formally designed derivative market that includes network representation and active participation by network service providers and end-users in that market.

Thus, efficient market-driven investment in generation requires equally efficient market-driven investment in network and end-use equipment. In principle, this could be achieved by a coordinated framework of nodal markets that covered ancillary services, spot energy and derivatives and was supported by measurements of market interval energy and key indicators of availability and quality of supply at each node. In practice, this approach may have to be limited to the transmission network and would only succeed with the active participation of end-users and network service providers.

Small participants could be supported by energy service facilitators or, as previously indicated, by regulated distributor-retailers that implemented “managed” local markets. Network investment decisions are particularly dependent on the efficiency of nodal spot and derivative markets, as they require rapid response to constrained conditions as well as reliable information about expected future spatial patterns of supply and demand.

Summary of barriers to efficient decision making

In summary, to efficiently coordinate participant decision-making, a restructured electricity industry requires a commercial framework that adequately replicates the full energy conversion chain from primary energy resources to end-use energy services, includes a representation of network impedances and flow constraints and incorporates important social and environmental externalities. The ideal commercial framework would support decisions with short-term inter-temporal links via ancillary service and spot energy markets, and decisions with long-term inter-temporal links via derivative markets. Generators, network service providers and end-users would all participate in the same framework. Energy service facilitators would replace electricity retailers.

Restructuring has yet to achieve a reasonable approximation to the ideal commercial framework, and there is some doubt that it ever will. At present, operating and investment decisions are made in a hybrid world of market-based and centrally planned decision making, with ambiguous boundaries between the two.

To date, electricity industry restructuring has attempted to quarantine operation and investment decisions for generation from those for network services and end-use. However this is not an accurate representation of the electricity industry and it has not delivered either economically efficient or environmentally sound industry outcomes. For example, there are problems with respect to end-use efficiency and demand management (particularly with respect to space conditioning), embedded generators, network operation and investment, and climate change impacts.

The failure to implement efficient retail markets is a significant contributor to these problems. Unfortunately the nature of the electricity industry requires high complexity in retail market design. Therefore, market design must be undertaken with care and small end-users should be given appropriately designed equipment, decision-making tools and support from "energy service facilitators".

Even with efficient retail market design, a question remains as to how far network services can be commercialised because the network provides a residual public good. This issue is discussed in the next section.

Commercialisation of network services

Network services that fall into two categories appear to be relatively easy to commercialise:

- Services that can readily be controlled independently of other network services and are amenable to trading in an auction-style market, preferably with competition from non-network options. For example, the use of a relatively small controllable DC link to provide arbitrage between two strongly meshed regional networks that each supported well behaved regional ancillary service, spot energy and derivative markets.
- Services that are not amenable to trading in an auction-style market but are clearly bilateral, and can be negotiated in a context that provides a reasonable balance of bargaining power. For example, connection services for a large factory that could negotiate with several network service providers or had a viable self-generation option.

Services that fall outside the above categories may be difficult to fully commercialise, but may be amenable to regulator-supervised commercial negotiation frameworks.

Network services that appear relatively easy to commercialise

Commodity-like services:

- The NEC defines market network service providers (MNSPs), which undertake arbitrage between regional energy spot markets on an unregulated basis. For a given transmission network, the more that regions can be clearly defined, the more that transmission network services can be made competitive by this approach. Limits to this approach include difficulties in defining regional boundaries, a requirement for adequate competition within each market region (including end-user participation), and the cost premium associated with the requirement for an MNSP to be able to control its energy flow.

- Research studies suggest that location-specific voltage-related ancillary services that can be safely averaged over a market interval could be made competitive through the introduction of voltage-value functions in spot energy market bids and offers. However this would be conditional on the implementation of a meshed network-wide set of nodal markets in which end-users actively participated, either individually or in an aggregated manner.

Services that are clearly bilateral:

- Shallow network connection for end-use equipment and generators (up to the point at which the network becomes a shared resource). Steps have already been taken to commercialise shallow network connection.

Network services that may be difficult to commercialise

Network services that appear difficult to commercialise are those that are intrinsic to the network as whole and shared by all network users; those that require rapid response; and those that involve activities that may be difficult to specify and audit. Examples include:

- The network's aggregation role that captures the benefits of diversity between the individual stochastic processes of demand and of generation. The aggregation property belongs to the network as a whole and it contributes to the performance of both rapid response ancillary services and the spot energy market.
- Minimisation of voltage variations in the face of rapid fluctuations in generation or demand.
- Network security and protection functions.
- Ancillary services related to waveform purity and phase balance.

For the time being at least, these network services should be classified as public good functions, although in some circumstances they may be at least partially contestable by distributed resources.

Contestability of network services by distributed resources

Because networks provide connectivity between generators and end-use equipment, most services that a network provides apart from those relying on its holistic aggregation function could, in principle, be provided by alternative actions that improve the match between the spatial distributions of generation and demand. Such actions are collectively known as "distributed resources", and include embedded generation (i.e. connected to a distribution network), reversible storage and demand side options such as peak load reduction, fuel switching or improved energy efficiency. For example, an embedded generator, installed and operated in a locality that remains a net load area, can reduce the need for network services that import energy and ancillary services from other locations.

However, to compete with a network's aggregation role, a distributed resource must provide the smoothing to supply-demand balance and ancillary services in its vicinity that a connection to the wider network would otherwise provide via its physical aggregation function. This may be a challenging task unless network capacity is constrained during normal operation or following a likely contingency, or if the network's aggregation role is ineffective due to strongly correlated stochastic processes in generation or demand, such as at times of summer or winter peak demand.

Contestability of interconnectors

The National Electricity Code allows Market Network Service Providers (MNSPs) to trade between regions when they are individually controllable. However, MNSPs are not always an appropriate solution:

- Region boundaries and interconnectors may not be neatly definable, and many factors can lead to interconnector flow constraints
- The technology to provide the required controllability adds cost and there is as yet little competition to provide MNSP solutions
- An interconnector control algorithm appropriate for energy spot market duty may not be appropriate for ancillary service duty
- Regional derivative markets are still immature, contributing to difficulties in establishing the commercial value of a potential interconnector project
- Network augmentation by regulated NSPs or inappropriate flow constraint representations may reduce or even eliminate the value of the arbitrage provided by the MNSP.

Settlement residue auctions provide a useful start to managing the risks associated with inter-regional arbitrage in energy spot markets. However, they provide incomplete hedges due to their reliance on energy flow between regions to generate cash flow, and because interconnector flow-constraints may have a wide variety of causes. As a general rule, it is not possible to provide a complete physical hedge between two nodes in a network.

Generators (in a net importing region) and end-use equipment (in a net exporting region) can provide competition for MNSPs. However in practice they are only able to provide competition for regulated interconnectors at times when network augmentation is being considered.

Contestability within regional transmission networks

Under the rules in the NEC, it appears unlikely that the services provided by regional transmission networks can be easily commercialised. Therefore it is important to sub-divide existing regions where it is reasonable to do so.

With adequate end-user participation, it may be possible to implement a nodal market structure for the meshed transmission network. This would implement a market at each zone substation for ancillary services, spot energy and derivatives, in which local generators and end-users would participate along with the transmission network service providers that could provide arbitrage with respect to other nodal markets. Distribution network service providers would offer a transmission market access service to end-users connected to radial distribution networks, and possibly provide an aggregation function for small end-users within the context of a "managed local market" (see next section).

With a nodal market structure of this kind, reliance on regulated transmission tariffs could be reduced and transmission network augmentation could become largely market-driven (with competition from distributed resources) even if transmission network service remained a regional monopoly. This appears to be a plausible long-term approach to enhancing the commercialisation of transmission network services.

Contestability within distribution networks

Nodal markets are unlikely to function well within radially operated distribution networks because of their re-configurable nature, the lumpiness of investment decisions and the interruptions to supply caused by distribution network faults. Therefore, it appears useful to introduce the concept of a "managed local market" based on the local distribution network connected to each zone substation.

Under regulatory supervision, a monopoly distribution network service provider would implement a managed local market for ancillary services, spot energy and forward risk management (effectively tradeable transmission market access rights), in which end-users and embedded generators would participate. Forward volumes could be developed using profiling techniques based on historical consumption patterns. Small end-users should be given appropriate decision making tools and be supported by energy service facilitators. A franchised energy service facilitator could be attached to the distributor and regulated during initial implementation of the concept and the function could later be de-regulated if competition was deemed to be adequate.

A model of this kind would enhance the market-responsiveness of distribution planning and increase the opportunities for distributed resources to compete with network augmentation or extension. However, except in rural areas, opportunities for distributed resources to defer investment in low voltage distribution feeders would remain limited compared to opportunities to defer investment in zone substations.

Boundary & transition issues

Under the NEC, regulated network service providers presently operate in the context of a competitive wholesale market in which large generators participate and potentially incompatible retail markets in which contestable end-users participate. Traditional tariffs still apply to small end-users.

However the holistic nature of the electricity industry means that there are important overlaps between the services provided by generators, networks and end-use equipment. Therefore, there are inevitable boundary problems between competitive generation, regulated network services and partly regulated end-use services. Improving the retail market design would allow network services to be made more competitive, reducing the boundary problems. Alternatively, aggregating small end-users to the zone substation level by assigning a franchise distributor-retailer to the distribution network supplied by each zone substation, would introduce an effective end-user presence into the wholesale market, allowing transmission network services to be made more competitive. With the latter approach, contestability between distribution network services and distributed resources would be a matter for regulation.

The most important transition issue associated with further commercialising network services is the political difficulty of either implementing effective retail competition for small end-users or returning to a regulated distributor-retailer model.

Prerequisites for commercialisation of network services

Because networks connect generators to end-users, the most important prerequisite for the commercialisation of network services is the introduction of either efficient retail markets or the creation of an effective end-user presence in the NEM wholesale market via a regulated franchise distributor-retailer charged with achieving least cost energy services for the small end-users in its assigned distribution zones. In either case, a service-value model for the economic regulation of networks should be adopted in place of the asset-value model that is presently used. The latter is a cost-recovery model in which network investment is justified by the "obligation to serve" after the key decisions that drive network investment have already been taken by network users.

Conclusions

Electricity industry restructuring in Australia has reached an important decision point. Network services remain largely regulated but they cannot be clearly separated from the competitive services currently provided by generators or those that could be provided by end-users.

Network services could be made more competitive if there was more effective end-user participation in ancillary services, spot energy and derivative trading. This would allow the value of more network services to be established by market mechanisms rather than by regulator assessment of asset values.

There appear to be two main alternatives for enhancing end-user participation – either implement effective retail markets (local markets based on zone substations) for small end-users supported by competitive energy service facilitators or franchise a distributor-retailer for the small end-users supplied from each zone substation. The distributor-retailer should be charged with implementing a managed local market and assisting end-users to achieve least-cost (in a broad sense) energy services. In the short-term, the regulated distributor-retailer model appears to be more plausible and may remain more appropriate in the longer term, particularly for rural areas where the likelihood of effective competition for small end-users appears to be low.

Both strategies would require interval metering for all small end-users that could record important indicators of supply availability and quality as well as market interval energy. Both strategies would also require the design of standardised ancillary service, spot and forward contracts for small end-users (forward volumes could be developed using profiling techniques) and the adoption of a service-value model for the economic regulation of networks.

Both strategies would require the introduction of the concept of an energy service facilitator to assist small end-users obtain energy services in a manner that was both economically efficient and environmentally sound. In both cases, a nodal market framework could be implemented over time for the meshed transmission network in which all generators and end-users participated either directly, or in an aggregated fashion via a transmission market access regime.