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Power System Planning

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39.1 The changing electricity supply industry (ESI)

Electrical power systems have developed over the 20th century to become the supplier of electrical energy to almost every household, factory, commercial building and activity in the developed world. Developing countries strive to emulate this achievement through attracting finance to build up their own infrastructure to stimulate their economies and to improve the quality of life for their inhabitants.

As with all industries, changing and improving technology through innovation, research and development has led to a change in the way power networks are planned and operated, initially as comparatively small local generation and supply networks, followed in the developed nations by more and more connections between local networks culminating in large continent wide grids with numerous large generating plant and components, high voltage systems and a supply to everyone requiring electrical energy. It has only been in the last 15 years from about 1985 that smaller operating units and private ownership of parts of the system has been seen to be an advantage.

39.1.1 Central planning

Power networks grew in capacity and extent in most industrialised countries through a centrally (government) controlled industry, often founded by treasury loans or sanctioned loans from the financial markets. This meant that with government involvement it was necessary to make a good case for the finance to be forthcoming to add to the present system or build anew to meet expected increase in electrical energy demand for all purposes. Consequently, centrally planned systems needed expert forecasting of demand at least 5 years ahead to design, manufacture and commission the necessary equipment and connections by cable or overhead line. Throughout the world the problem over many years was to achieve good forecasts which turn out to be dependent upon economic cycles and gross domestic product (GDP) which are well known for being extremely inaccurate, particularly in the 5 year time scale. The inevitable result has been that the ESI in most countries has been underdeveloped and never matches supply to demand, or overdeveloped where plant has been underutilised leading to inefficiencies and a higher price for energy than necessary. After 30 or 40 years from the 1940s to 1980s of attempting to make central planning work, the concepts of economic efficiency and plant installation by funding through the principles of the investment market—as in the oil and gas industries—was seen to provide a more acceptable way of achieving the desired objectives. This has produced a movement by many governments to deregulate and restructure the ESI such that central planning is no longer the norm, but private finance is encouraged to take the risk of getting a return on investment.

39.1.2 Vertical integration of generation and supply

Under central planning and government control, it was considered necessary to plan and operate the network as a unity such that the production, distribution and sale of electricity was either organised and run by one utility or each part had statutory obligations to ensure fairness and constraint on profit taking. Most countries, including the USA, ensured that utilities could not act as monopolies but only charge a reasonable tariff to obtain a regulated return on capital invested. It became the practice for utilities to serve defined areas or populations without fear of competition and to purchase energy from their own generation or interconnected power network. This was known as 'vertical integration' and prevented other suppliers encroaching on the supply territory of another utility. If tariffs were set by governmental edict or statutory control, there was obviously little incentive for utilities to innovate or compete on price. To overcome this obstacle, many industrialised countries with a mature and reasonably adequate energy infrastructure looked for ways of using market competition to reduce energy tariffs and to provide an improved service to the consumer. This has produced 'deregulation' of the ESI.

39.1.3 Deregulation and restructuring

These are the 'buzz' words for a world-wide movement to improve consumer service and reduce prices in mainly the industrialised nations. It also means that controlled planning is no longer required—the necessary improvements in service, quality and price to produce satisfied customers being obtained through 'market' forces. It was quickly realised that if generating plant could be allowed to compete country wide on price and the transmission and distribution network could deliver the commodity (energy) to any part of the country, then competition to supply individual consumers could also be encouraged. Consequently, the break-up of the generation utility monopolies by selling shares (if government owned) or trading generation ownership on the stock market would achieve the desired ends. On the supply side allowing suppliers to encroach into others' territory would also produce competition with (hopefully) low prices and improved service. This was the desired deregulation and restructuring with no government involvement in setting prices provided that 'level playing field' competition could flourish.

Unfortunately, the power system network which enables the generator owner to sell energy to the suppliers was almost a natural monopoly in that it would be prohibitively expensive for another entrepreneur to construct an alternative supply network. Hence a *regulator* would be needed to ensure that fair prices were charged by the owners of the power network for energy transportation. The net result appears to be that generation and supply through private or market investment has obviated any planning needs through government forecasting but the power system can be made adequate for consumers through risk management implemented through many utilities.

39.1.4 Least cost planning

With a deregulated ESI, no longer is there a planning authority but all investors need to plan for their own investments and expected returns. This implies that companies who are thinking of financing a venture into the ESI, must consider all options open to them and estimate the risk and return on investment by considering the following aspects:

- the minimum cost investment to meet the desired objectives over a given period;
- the robustness of the proposal against likely changes in market rates, social climate, environmental constraints, etc.;
- likely level of co-operation between the company and the customers being served; and
- the financial viability of the whole proposal, including the attitude of the shareholders, the regulator and the government.

In theory, any investment in new plant (generator, transmission facility, supply services) should not occur until the cost of alternative measures to achieve the same objectives is equivalent to new plant costs. In practice, new plant investment may be required because of new developments, economic boom, improved supply security, availability of new technology etc. It is against these criteria that new investment will need to be measured.

39.2 Nature of an electrical power system

39.2.1 Electricity supply

All countries now have available some supplies of electricity to connected consumers. In many industrialised countries a nationwide grid or distribution system is installed so that generating plant can be 'pooled' through interconnections to supply customers from industrial/factory complexes down to the smallest residential consumer, perhaps with a single light or TV set. As electrical energy is not easy to store, except by converting it to some other form of easily stored energy e.g. water pumped to a higher reservoir, the generating plant output must always match instantaneously the demand of the loads plus the losses (hopefully less than 10%) in transporting and delivering demanded energy (units of kWh). For many good reasons, most small consumers require their supply at a low voltage (230 V in Europe, 110 V in USA for example) whereas to keep losses low, electricity needs to be transmitted over any distance at a high voltage (400 kV in Europe, up to 700 kV in US/Canada). Generation, on the other hand, is most economically done at around 20 kV thereby requiring a step-up in voltage to the transmission system and a step-down in voltage for distribution to the myriad of small (mainly residential) consumers. This transformation is readily done by high efficiency *transformers* which require, due to Faraday's law, an alternating voltage at 50 Hz in Europe, Japan, Australia, etc. and 60 Hz on the American continent. To keep material costs to a minimum, transmission and distribution is best done using a *3-phase* system but only a *single-phase* supply is required by small consumers. Large and intermediate consumers such as industrial processes, factories, large buildings and hospitals etc. are most economically supplied at a higher voltage than to small consumers, at between 10 to 20 kV.

Consequently, many distribution systems consisting of step-down transformers, cable or overhead lines operate at this voltage and only the final, comparatively short connections to individual small consumers, operate at 230 V or 110 V, usually by tapping off from a 3-phase system.

39.2.2 Transmission

Part of a typical generation and transmission network is depicted as a single line diagram as in *Figure 39.1*.

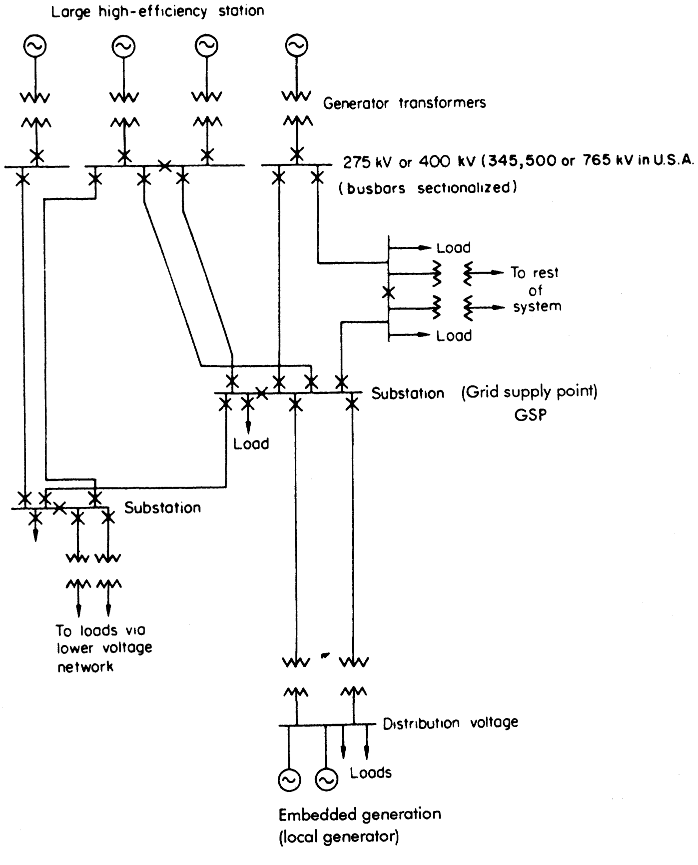

Figure 39.1 Part of a typical generation and transmission network. (Reproduced by kind permission of John Wiley & Son, Ltd)

It should be noted that generators are interconnected by a 3-phase system and it is essential that they run in synchronism with each other. If a generator cannot remain in synchronism due to a fault, then it must be disconnected by its circuit-breaker otherwise the whole system could collapse. In the figure, substations enable circuits to be switched and alternative routes are available if a circuit needs to be withdrawn for repair or maintenance. Distribution systems are fed from the high voltage network through step-down transformers and increasingly there are smaller generators 'embedded' in the distribution network adding to the combined energy output of the synchronised system.

In a deregulated ESI, the generators could be owned and operated by different utilities, the transmission lines and substations owned by other investors and the supplies to the distribution systems bought under contract to private distributors or suppliers.

Increasingly, for undersea connections or for connections between networks not in synchronism, high voltage direct current using semi-conductors as a rectifier one end and inverter the other is being used. Such connections should be considered as alternatives to a.c. connections.

39.2.3 Distribution

Medium and low voltage distribution systems vary in their design and layout depending upon the locality being served.

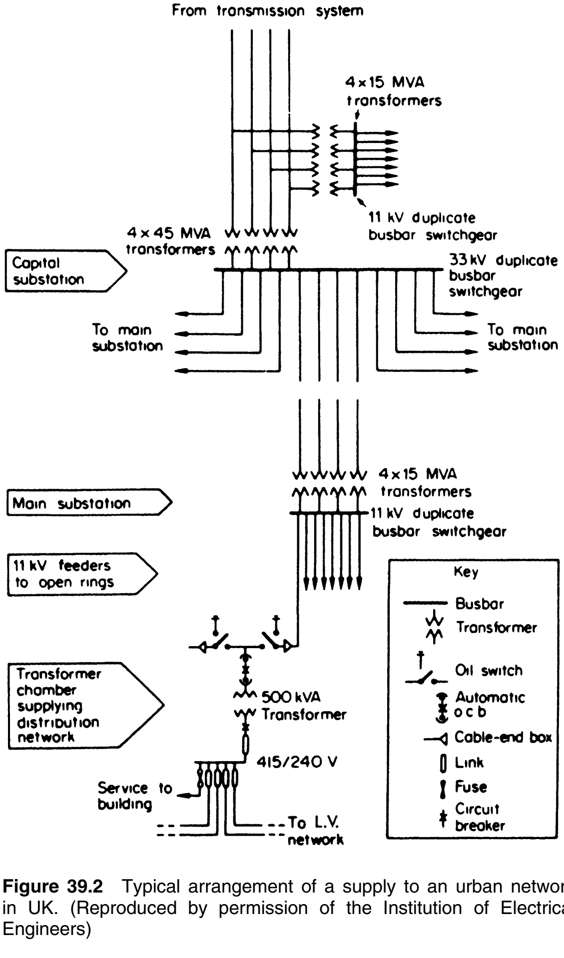

Figure 39.2 Typical arrangement of a supply to an urban network in UK. (Reproduced by permission of the Institution of Electrical Engineers)

In urban areas, where consumers are numerous and concentrated, an underground network with closely spaced step-down transformer substations are installed sized to meet the maximum expected demand after taking into account the average diversity of customer use. *Figure 39.2* depicts a typical urban network where each single line represents 3 phases contained within a single under road cable.

Because of the complexity of protecting the system if it was fully interconnected, it is usual to operate it as a radial system fed from the primary substations but allowing circuits to be supplied by alternative connections if any circuit is disconnected under fault or maintenance conditions.

For rural areas with sparsely sited consumers in farms or small villages, most supplies are stepped down by small pole-moounted transformers as close to the consumer as possible fed from a radial circuit. Fuse rather than relay operated circuit breaker protection is employed for cheapness and reclosing circuit breakers in the primary substation ensure that supplies can be quickly restored to healthy circuits once a fuse has blown because of a fault.

Figure 39.3 shows a typical rural distribution system in which section points allow manual reswitching to restore supplies after fuse disconnection. Overhead lines, either 3 phase or single phase, is the norm thereby allowing quick repair with a suitably equipped crew.

39.2.4 Loads

Consumer demand in a power system is often called a load and, of course, it will vary from hour to hour, day to day and season to season. Typical daily load curves aggregated over the whole England and Wales system are shown in *Figure 39.4*.

As previously remarked, the total generator output must match this demand and this requires the generators to be flexible. In practice, to maintain as high an efficient output as possible generators wish to run at full output or be off-line so the system operator instructs plant to synchronise and desynchronise at pre-planned times worked out by some economic scheduling algorithm. At times when the demand is expected to fluctuate by ±5% or so within minutes (as could happen in a countrywide event when kettles or cookers are switched on/off in co-ordination by a TV programme) then a number of generators, particularly those with quick response, will be scheduled.

If the demand curve of *Figure 39.4* is plotted in descending order of magnitude as in *Figure 39.5*, the resulting diagram depicts a *duration curve*. Over a year of operation this curve indicates the *load factor* at which various kinds of generating plant can be expected to operate.

Normally the plant having the cheapest price per kWh would operate at base load and the peaking plant would operate on very small load factor around the peak demand. Other plant, depending on its characteristics and production costs, would be expected to run at the intermediate load factors, probably generating during the day and shutting down at night (known as *two shifting*).

In interconnected systems or power pools where energy trading is allowed, the operation of the system is much more complex. In this case, existing generating plant may find that it is unable to rely on base or intermediate load operation and must be installed and run according to its contracted output portfolio rather than in any economic sense. Plant without sufficient contracts to sustain their operation could therefore be isolated and eventually shut down, whereas newly installed plant with long term contracts could take its place. The availability of long term

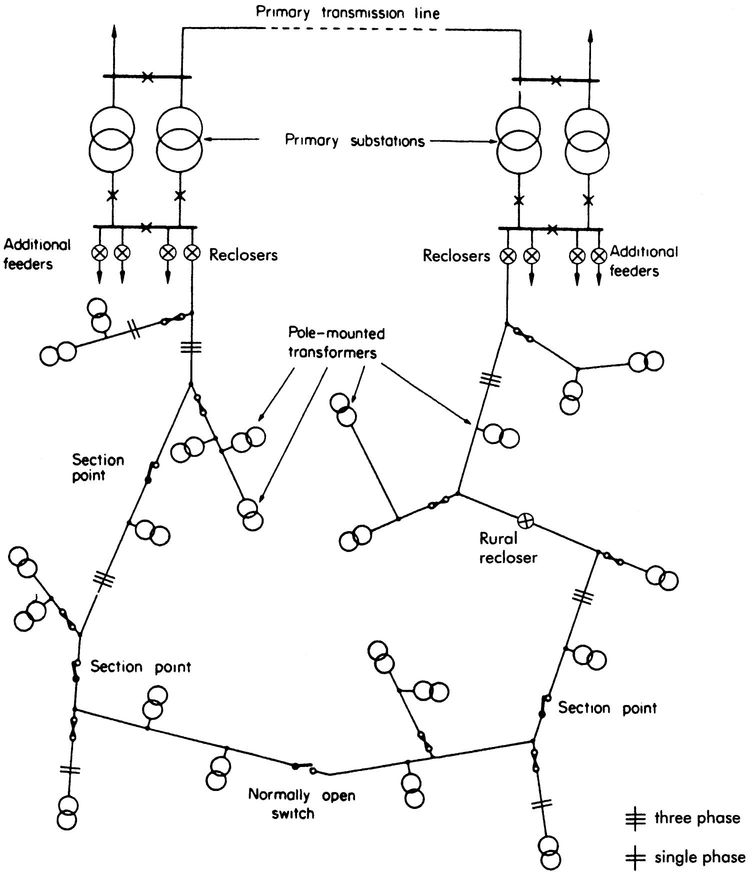

Figure 39.3 A typical rural distribution system at 11 kV with step up and step down transformers, the latter protected by fuses

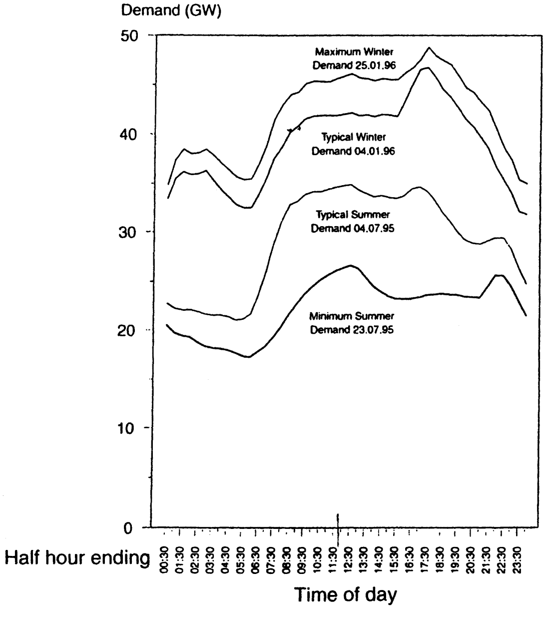

Figure 39.4 NGC summer and winter demands for 1995/96 (not weather corrected). (Reproduced by permission of NGC)

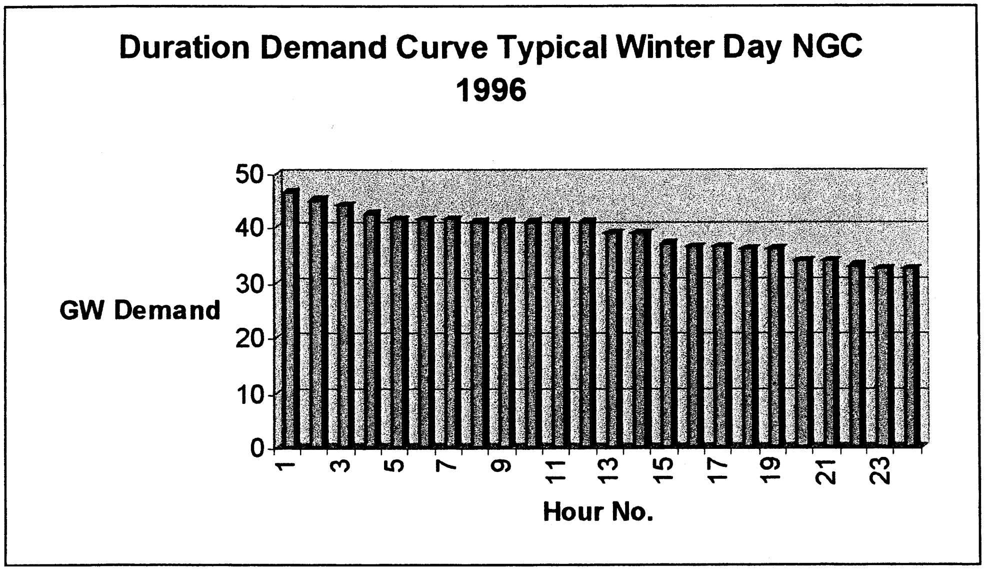

Figure 39.5 Demand duration curve for typical winter demand on 04.01.96

contracts on both the fuel supply side and the output energy side is likely to be the dominant feature of planning in the future.

39.3 Types of generating plant and characteristics

Details of particular types of generator are given in other sections of this volume. Here, the main characteristics for planning purposes are summarised to provide a comprehensive picture.

39.3.1 Steam turbine

The steam turbine, running at 3000 rpm for a 50 Hz output or at 3600 rpm for a 60 Hz output is the traditional work horse in most power systems.

It can be built in sizes up to 1200 MW when fuelled from coal, oil, gas, or nuclear sources. Coal fired plant requires quite expensive delivery, stocking and handling facilities compared with oil or gas thereby making it more difficult to finance initially although since the fuel is abundant in many countries and can perhaps be quarried rather than deep mined, the cost per MWh of output can be very competitive. Since most solid fuels contain sulphur, flue gas desulphurisation equipment may have to be statutorily fitted adding approximately 20% to the overall cost of the plant. The disposal of ash and gypsum (from the desulphurisation process) also has to be considered.

On the other hand, oil firing could also require some flue gas clean-up if sulphur is present but except in oil producing countries oil is relatively expensive compared to coal, but it is useful as a quick start (30 mins) source for peak lopping. Direct gas firing to raise steam is now a strong competitor to oil or coal, particularly if connection to a gas pipeline is inexpensive and gas can be used in a dual fired boiler to back-up coal firing dependent upon arbitrage costs. The problems of using nuclear reactors for steam raising are well known although some of the steam driven turbine generators are the largest units constructed.

All steam driven turbo-generators require cooling water to create a high vacuum in the low pressure turbine for maximum efficiency, some of which can reach 40% dependent upon the highest temperature and pressure that materials can tolerate. It should be noted that combined cycle gas turbines (see later) also depend for their high operating efficiency on pass-out steam turbines with cooling water condensers as in traditional steam raising plant. An abundant source of make-up water and water recirculation in the sea or inland lake for cooling purposes can often be an advantage compared to the need for large cooling towers or fan driven coolers in smaller plant.

39.3.2 Gas turbine and diesel

Since about 1980 the development of gas turbines running at 6000 rpm plus in 100–200 MW sizes because of the advances in high temperature blade material has enabled this combined cycle form of plant to generate at efficiencies of up to 60% and in comparatively small sizes. As this type of turbine is considerably smaller than a steam turbine of comparable power output, it can be started and stopped much more rapidly thereby producing the potential of being used as intermediate generation. As the site area necessary is also much smaller than required for steam boilers and turbines, it can be sited much closer to load centres or inside the curtailage of industrial complexes, thereby reducing the need for transmission to energy over some distance with consequent losses.

In the 1990s, combined cycle gas turbine (CCGT) had begun to provide the base load because of the comparative cheapness of gas as a fuel and the high operating efficiency.

As coal fired and nuclear plant had reached the end of its economic life, CCGT plant was being used more to supply base load, but during the early 21st century with the increasing installation of CCGT displacing older plant, intermediate (two shift) loading is becoming more usual. With two or more gas turbine driven generators whose waste heat raises steam for conventional generators, the flexible output obtained by varying the number of GTs is of prime importance to meet contracted varying output over the daily cycle. As the CO_2 produced by a CCGT with gas firing is only 55% of that of a similarly rated coal or oil fired plant, its popularity with environmentalists is evident. Note also that 10% overload for short periods is possible to meet short peaks and/or aid system recovery following a generation loss. Added to all these advantages is the comparatively low cost and short (2 years) installation time, particularly for CHP schemes, its use in power system planning is assured. An alternative to GTs in small CHP schemes (up to 50 MW) is that of diesel plant running at slow speed but overall efficiency of 90%.

39.3.3 Renewables

39.3.3.1 Hydro power and pumped storage

Until fuel cells or rechargeable batteries become economic and reliable, the well known water turbine driving a multipole generator at comparatively low speed is still a valuable fast response unit that can act as reserve or regulating output, particularly at peak periods. Combined with pumping action, either using the coupled turbine in reverse mode or a separately coupled pump, water can be stored in a high level reservoir at low energy cost periods for use during peaks or emergencies. Overall the combined pump-generate cycle can run at up to 70% efficiency, implying that provided the difference between peak and off-peak energy cost is 35% or more, a pumped storage plant can be run at a profit. Retrofitting hydro-plant with pumping equipment is another possible option, particularly as the first cost of hydro can be very high. Storage is essential if the renewable energy source is intermittent as described in the next subsections.

39.3.3.2 Wind generation

A popular renewable source of energy is from the wind, particularly in temperate zones where most days have a wind blowing. The economics of wind energy depend upon the range of wind speeds between the minimum ‘cut-in’ speed for the wind generator and the maximum speed that the wind blades are designed to withstand. A high average wind speed as usually found on exposed high ground is obviously an advantage, indicated on charts by ‘isovent’ contours. The visual impairment of any scheme needs the preparation of impact statements to satisfy the local environmental lobbies and the connections into what is essentially a rural distribution network requires careful design in conjunction with the distribution owner. Problems of voltage control, reverse current protection, safety of distribution personnel when sources of energy other than from the primary transformer are present in the network, all require consideration. Wind farms consisting of 20–30 wind turbines mounted on 30–50 m masts having 2 or 3 bladed sails, rotating at 100–150 rpm to produce up to 600 kW per turbine are now common. Reliability has increased and the cost per kW reduced as experience has been gained and selection of appropriate materials has improved. The output cost per kW in year 2000 is now, on average, twice that of coal or gas fired plant, but as the energy (when available) is fed directly into the local distribution system, thereby avoiding both transmission and the bulk of the distribution losses and use-of-system costs, the energy price to the small consumer is becoming competitive. It is possible that consumers are willing to pay a premium for energy said to come from a renewable source. In the UK, a good site can produce 1800 kWh of energy per kW installed in a year.

39.3.3.3 Solar power

In tropical areas and favourable temperate zones, power from the sun is becoming more and more flexible, either by using mirrors focused onto a steam raising boiler driving a conventional turbine or through the employment of solar panels with power electronic conditioning equipment to convert direct current into alternating current. The mirrors require angle positioning and tracking equipment for economic output and the area occupied can be comparable with that for a solar panel photo-voltaic array. Maintenance of mirrors and solar panels is required especially in dusty/desert zones. Installation of 10 MW or so are now becoming economically viable. Many of the considerations for wind energy installations apply to solar also.

39.3.3.4 Tidal, ocean temperature gradient and wave power

Tidal power in large estuaries where a suitable tidal range is available requires horizontal, two-way flow turbines for energy production. It is comparable in cost to hydro-electric schemes, implying that long construction times and up-front financing is necessary. It has not been a great success anywhere in the world because of the impairment of the natural environment likely to ensue. Using the temperature difference between surface water and that at 500–800 m deep could produce energy from a specially designed turbine at 3 to 4% efficiency but would require vast quantities of piped sea water needing large underwater structures not yet attempted. Wave energy, close to rugged shorelines is a prime example of an obvious and visual source if only it could be reliably and economically harnessed. The variations in wave height and strength over the seasons are well known and the ability to cater for the severest storm conditions by man-made structures is fraught with difficulty. Research into robust shore structures using the inflow and outflow of the wave energy to drive air through a reversible turbine is continuing.

39.3.3.5 Other renewables

There is some uncertainty as to exactly what should be regarded as a renewable resource. Wood or straw burning boiler plant for steam raising is acceptable—provided the wood is obtained from a managed forest where replanting on a scheduled basis is undertaken. Refuse incineration and landfill gas driven plant may or may not be classed as renewable depending upon the source of the bio-fuel. Such plants are increasing in number and extent and their assimulation into the local electricity supply system must be planned. Sources such as geothermal energy are valuable in suitable locations and as drilling becomes possible in deeper boreholes at reasonable cost, such ‘renewable’ sources using the heat of molten magma within the earth’s crust become attractive.

39.4 Security and reliability of a power system

In industrialised countries, a high level of reliability of supply is expected amounting, on average, to not more than 60 min loss of supply (blackout) per year. In addition, voltage sags (dips), momentary interruptions or voltage surges should not cause interference with a consumer's installation. This condition is becoming much more onerous with the increasing use of power electronic equipment in which nuisance tripping can lead to shut-down of an entire industrial process. Consequently, considerable attention is now focused on *power quality* and the elimination of unwanted harmonics in the system. Many consumers with sensitive electronic equipment are encouraged to safeguard their vital equipment with an auxilliary uninterruptible power supply (UPS) using a battery or fly-wheel generator store. In general, the reliability of supply from generator to consumer depends upon the *availability* of generation plant, transmission and distribution equipment, the ability of the ESI to install sufficient generators to maintain a suitable margin of reserve capacity taking into account maintenance and forced outages and the design of the transmission system for security and continuity of supply to the consumer. On availability, all plant requires periodical planned outage for maintenance purposes and hopefully this aspect of planning will be done in conjunction with the system operator. Maintenance procedures are best developed from careful diagnostic measurements and statistical records including breakdown incidents plus advice from manufacturers. An increasing and desirable trend is towards more on-line diagnostic measurements from which possible breakdown occurences can be predicted, particularly if this leads to longer periods between maintenance or forced outages.

On the transmission system, networks should deliberately be designed to provide alternative paths for energy flow in the event of one (or sometimes two) of the *n* circuits being forced out because of a fault, lightning disturbance or vandalism. This is known as *n*-1 (*n*-2) security and could be a condition laid down by the regulator in granting a transmission licence. Incidentally, this 'overprovision' of circuits compared to that of a just 'adequate' system leads to fewer losses and hence reduced cost of operation.

On the distribution system, the expense of providing duplicate circuits is not justified except perhaps in densely populated areas such as cities and industrial complexes. Again statutory requirements or the regulator will lay down the 'target' frequency of interruptions and the time allowed for restoration, usually by designing the system for back-up re-switching through strategically placed isolators or circuit-breakers. The target 'restoration' time should account for proficient remote monitoring and alarming of supply conditions and the deployment of standby repair crews. Most countries have standards on demand levels and the security required dependent upon the MW disconnected through circuit outages.

39.5 Revenue collection

Of prime importance is the ability to meter and collect the dues from the various parties in the generation and supply chain. In a vertically integrated or government controlled power system, the most important revenue to be collected is from the final consumers. This is usually achieved through the reading of a customer meter, belonging to the power authority, and the sending out of a bill according to the agreement between the authority and the customer. Tariffs can be for units (kWh) consumed between the meter readings according to some scale, or, for the larger consumers, kVAh or kVArh and peak kW can be included. It must be emphasised that in a restructured ESI the final consumer may be supplied by an organisation who own no physical equipment but who make bulk purchases on the energy market and retail it at a negotiated price. For small (mainly residential) consumers this price must be published, but for larger (commercial or industrial) consumers this contract may be confidential.

The supplier must, of course, pay the transmission and distribution system owners for the delivery of the energy, thereby requiring not only metering in all parts of these systems but also an approved use-of-system charge as set by a government authority or a regulator. Finally the generators must collect revenue from the suppliers for their contracted energy as metered by an independent authority and assessed through an appropriate regulated formula. It is obvious that the measurement and collection of revenues is now a complex business requiring careful organisation and the taking of many millions of measurements each day for half-hour or hourly slots. Automated meter reading and formulaic calculation is absolutely necessary to reduce the costs of collection and billing if the final price of energy is to be restrained.

A continuing problem is the balance between introducing 'smart' meters with a communication channel between consumer and supplier or continuing with manual meter reading on a periodic basis perhaps interspersed with estimated readings. The former with all extra costs included can amount up to 20% of a residential consumer's bill although for larger consumers with bills of £1000 p.a. or more the cost of the new meter and associated communications can soon be recovered in the tariff. A meter reader can be expected to call on 100 to 150 customers a day dependent upon density of housing whereas a smart meter with two-way communication can be interrogated at least once a day and the payment notified immediately to the customer followed by direct debt to an agreed bank account. It was the practice to install pre-payment meters for poor paying or rapid turnover customers but the cash collection adds to costs and makes it difficult to give discounts and thereby reduce bills to the poorer members of society.

In developing countries where energy per household is extremely small, a fixed standing charge with fuse limitation of maximum demand is possible to save on collection costs. Where demand is for fixed and calculable times, such as street lighting etc., then an agreed monthly payment is preferable to avoid metering costs.

39.6 Environmental sustainable planning

No power system plan for a 'green-field' site or extension to an existing network can avoid careful and in depth consideration of the effect on the environment. It is expected that most governments have introduced or will introduce a strategy for reducing carbon dioxide and polluting gas emissions from electrical energy producers. This strategy not only requires energy producers to be more efficient than in the past but also expects the consumers—both large and small—to reduce considerably energy use of all kinds. Unfortunately, electrical energy is perceived to be the most polluting source because of the large power stations evident around the country and also because of the relative inefficiency of end use in all kinds of industrial plant, air conditioning and cooling, freezers, refrigerators and home heat losses. Estimates of possible reduction in CO_2 emission per kWh of electrical energy over the next 10 years are up to 20% and by careful design and encouraging awareness of the problem, more reductions could be possible.

Although pollutants produced by electrical energy production can be mitigated by design, the extra cost must be borne by the purchaser e.g. flue gas desulphurisation on a large power station can add 20% to its capital cost plus about 10% to the running costs, making it uneconomic compared to existing stations. One answer, now being introduced by many governments, is the purchase of an emission limit licence for each installation, which if not fully taken up each year can be traded like any other asset. The aim would be to control total emissions such that local atmospheric conditions could be stabilised and reduced.

For carbon dioxide emissions leading to global warming a similar 'carbon tax' on fuel use is proposed. Whilst the cost of CO_2 entrapment at source is tremendously expensive at present (+80% estimate for a power station) the tax would pay for more research and development leading eventually to power products such as renewables and fuel cells in which no CO_2 is emitted. The aim is to move towards non-polluting producers, including zero CO_2, and to use resources that will sustain the ecology of the planet and continually improve the quality of life for all.

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