Can Nuclear Power Be Flexible?

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Abstract

This paper raises the issue of whether nuclear power can play a flexible role within an electricity system. It does not deal with the issue of whether nuclear power should play such a role, but it does examine why in most cases it does not. We introduce the basics of nuclear physics and reactor designs sufficient to cover the technical issues of relevance. We then identify the key technical issues that must be tackled in order to load-follow with nuclear power. We assess the flexibility and load-following ability of current and future promising reactors. We confirm that modern Generation III and III+ are technically capable of flexible operation. To explain why nuclear power is almost exclusively used as baseload generation, we look at power market economics. As a result, we conclude that despite some technical abilities, nuclear power plants are preferentially used for baseload generation for economic reasons and will continue to be used in this way for the foreseeable future.

Introduction:

Amid the usual political and economic debates surrounding energy policy and electricity (including e.g. security of supply, CO_2 emissions reduction and affordable electricity), several countries are re-examining the benefits of nuclear power. As a result, one encounters assumptions concerning the perceived or real lack of output flexibility of nuclear power plants (NPPs), and its relatively weak role in ensuring grid stability. For instance, in the UK, in the 2006 Energy Review, the following statement is made:

… [Nuclear Power] has the disadvantage that it cannot easily follow peaks and troughs in energy demand.

Such a statement implies that nuclear power is incapable of load-following for technical reasons. Consequently we assess here whether such an assumption is valid or useful: Is nuclear power flexible? Central to such flexibility is the notion that in principle both demand and supply sides should be capable of “operational flexibility”. In reality demand-side management plays a relatively minor role in grid stability and practical responsibility for stability rests with generation and ancillary services.

1. Technical aspects:

If nuclear power is to be considered for a major role in decarbonising the UK electricity system and if, as some advocate, it is to operate closer to the margin of the UK electricity system, then it is important that policy-makers and industry strategists have a proper appreciation of the actual level of flexibility of modern nuclear power plants. We therefore ask: what are the main technical issues to be considered if we are to fairly assess the ability for a NPP to load-follow? And are all the nuclear designs equally flexible?

A specific aspect of the challenge is: can, and should, NPPs comply with specific grid requirements [2,4], in terms of frequency control, load-following and spinning reserve capabilities [3]. To better understand the technical implications, especially in terms of power control, it is useful to consider the relevant nuclear physics, engineering and design science. In order to be able to assess the flexibility of these reactors, one must consider the basics of nuclear power control.

1.1 Criticality:

The key parameter of nuclear power control is the reactivity ρ [6]:

$$\rho = \frac{k-1}{k} \quad \text{with } k = \text{Effective multiplication factor} = \frac{Rate\_of\_neutrons\_produced}{Rate\_of\_neutrons\_lost}$$

The *Rate of neutrons lost* is mainly given by the rate of neutron absorption plus the rate of leakage of neutrons from the reactor core. The *Rate of neutrons produced* is the rate of neutrons created by the nuclear fission chain reaction. In order to maintain the reactor in a stable “critical” state (denoted by $k=1$), nuclear power plant designs provide complex feedback mechanisms that ensure a tight control of reactivity, ρ.

1.2 Theory of power control:

Key to the flexible operation of nuclear power plants is the ability to adjust quickly, but evenly, electricity output; that is to say, to adjust output power without overly disturbing the neutron flux distribution within the reactor core. The literature reveals five basic ways to change and control the reactivity of a nuclear reactor [7]:

- Adjust the amount of fissile material in the reactor:
- Adjust the neutron leakage from the reactor:
- Adjust the rate of primary coolant circulation:
- Adjust the amount of neutron absorption within the reactor
- Deliberately insert absorption materials into the reactor core

The fifth method is the usual approach adopted either via the insertion of neutron-absorbing control rods or by the injection of liquid burnable poisons into the coolant/moderator circuit of a water cooled reactor [1]. In addition, some uncontrolled poisoning products (mainly Xenon-135) can also affect the core reactivity.

1.3 Operational flexibility assessment:

In principle, all nuclear reactors might reasonably be regarded as having some capacity to follow load. In practice, however, the ability to meet grid needs efficiently and safely is restricted to a certain set of design types. As we shall see some reactor types that might conceptually be regarded as being suitable for load following are excluded (for technical engineering reasons) because they have not been subjected to necessary safety-related testing and licensing.

1.4 Design Attributes:

In this paper we shall consider existing graphite moderated gas-cooled reactors, future high temperature gas-cooled reactors, Pressurised Water Reactors (PWRs), Boiling Water Reactors

(BWRs) and heavy water reactors. The category of Light Water Reactors encompasses both PWRs and BWRs. In order to know why some reactors are able to ramp their power at a rate up to 5% per minute (or even 10% per minute ramps over a limited range of power) [10], and to understand why some are capable of starting-up quickly after a long period of partial-load operations we should consider the following factors[1]:

- Reactivity control systems:

In order to understand the ways in which plant operators can control electrical power output it is helpful to start with a consideration of the most widely used tool, control rods[2]. Their effects are indeed much faster than injected diluted neutron poisons, such as soluble boric acid. Roughly speaking, the more control rods a reactor has, the better its flexibility (especially its frequency control capabilities). It is important to note that while most reactor types have control rods for reactor shut-down control, these rods are not optimised for controlling flexible reactor power levels. These conventional rods are known as ‘black rods’ indicating their complete absorptive capacity for stopping the passage of fission neutrons. Flexible reactor operations are facilitated through the use of special reactor control rods known as ‘grey rods’. These rods do not completely absorb the fission neutrons that try to pass through them. For load-following manoeuvres, a clever management of both control rods and soluble boron is found to be optimal [5]. The exclusive use of control rods for output power control would have negative consequences, such as: flux distribution disturbances (see figure below), component materials fatigue, mechanical wear, and adverse impacts on fuel burn up. Many of these difficulties arise for the fact that, for instance, output electrical frequency control involves very many low-amplitude rod movements (up to several hundreds a day), which may limit the lifetime of control rod mechanisms[3] [3].

- Temperature inhomogeneities and fluctuations in the reactor core:

Temperature (as well as pressure) fluctuations are crucial to assess the thermal constraints and fatigue for the core vessel and other components. These difficulties are exacerbated by load following operations. Assessments of pressure with temperature and along the height of the reactor vessel are especially important in this regard.

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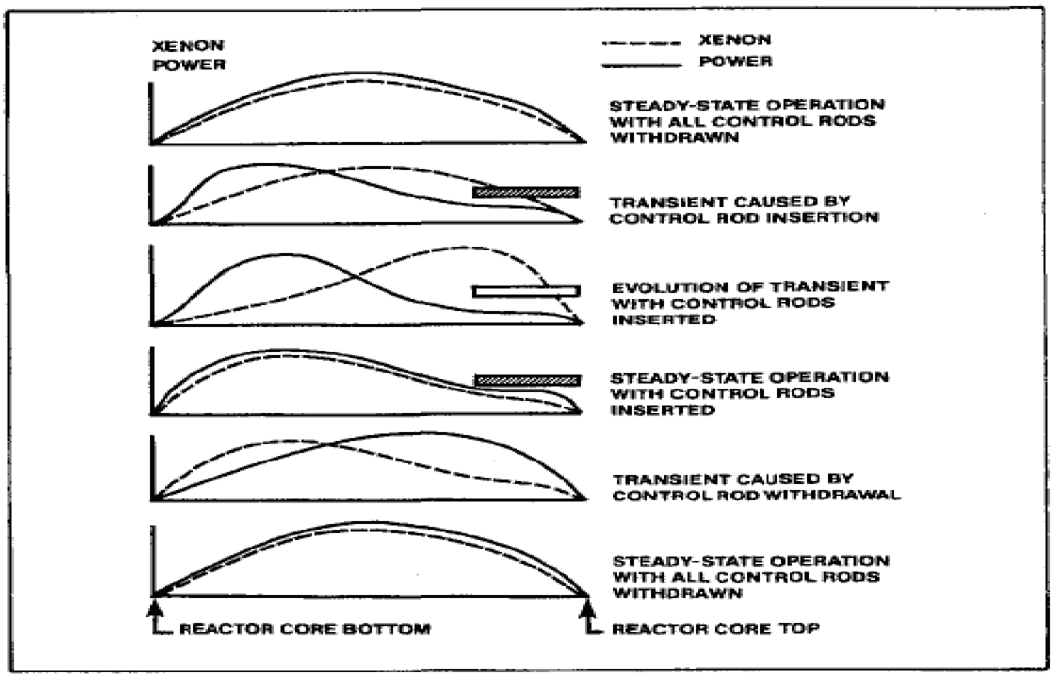
[1] With thanks to Dr Geoffrey T. Parks, Cambridge University Engineering Department.

[3] For further data on the real time frequency control operated by NGC, please see: http://www.nationalgrid.com/uk/Electricity/Data/Realtime/

- Xenon Poisoning:

The uncontrolled creation of poisoning products such as Xe-135, especially when reactor output is reduced, is also a key issue. It can imply delayed local flux distribution disturbances (see figure below). This difficulty includes the possible formation of "hot spots" in the core that could further jeopardize reactor stability. We shall therefore examine the power density of the reactor, because the greater it is, the greater the effects of xenon on power distribution. The power density of a reactor can be defined as thermal power generated per unit of reactor volume.



Effects of control rod movement
and xenon poisoning on axial power distribution

Figure 1: Effects of control rod movement and xenon poisoning on axial power distribution (Source: Framatome [3])

- Fuel enrichment:

While it is a relatively minor factor, it is worthwhile to note that higher levels of fuel enrichment (i.e. higher levels of the fissile isotope uranium-235) increases the reactivity of the core. Therefore fuel enrichment is an important design-specified aspect of the reactor. Reactors with higher levels of fuel enrichment are typically more difficult to control and have core neutron flux distributions that are less well suited to flexible operation.

The load following capabilities of a reactor stem largely from pre-construction design choices, including such issues as design for thermal and mechanical stress. The lifetime of a reactor used for load following is also affected by the care taken by reactor operators concerning their use of control rods and/or soluble boron.

1.5 Case studies:

- Gas Cooled Reactors:
    - UK Magnox:

In the typical Magnox design, power changes are achieved, noting the negative fuel temperature coefficient, by varying primary coolant flow, and also by inserting B_4C (Boron carbide) loaded control rods. The negative fuel temperature coefficient ensures that the cooler the reactor the greater its reactivity. Moreover, the Magnox system's use of natural uranium fuel, the reactor design's very low power density and its use of automatic control for local rods positioning (mitigating against local Xenon spatial oscillations), allow one to imagine that conceptually Magnox reactors might be suitable for load-following operations.

However, in the UK context, load following capability was not a specified requirement when the Magnox reactors were designed. As a result, no significant investigation has been undertaken to assess the potential flexibility of Magnox reactors. In fact, and in addition, plant operators have seen enough over the years to know that this reactor design has rather poor load-following capabilities, especially because of a susceptibility to Xenon poisoning, and its low temperature and pressure limits only permit very slow and small load variations[4].

Furthermore, the Magnox design suffers from a constrained and relatively low fuel temperature. In order to ensure best possible energy efficiencies from what is in principle a

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[4] With many thanks to David Ward (Magnox Electric Ltd)

low efficiency design and for commercial reasons, Magnox reactors have been operated as baseload supply with constant fuel temperatures [1].

- Advanced Gas-cooled Reactor (AGR):

Drawing on prior experience with the Magnox reactors, in the 1960s the UK continued with gas-cooled and graphite moderated designs for the second generation of British nuclear power plants – the AGRs.

Particular examples of knowledge transfer into the AGR programme include:

- Heat exchanger design
- Graphite moderator with its associated high thermal storage capacity
- The reactivity control systems (e.g. B_4C rods and coolant flow rate).

However, unlike Magnox, the rapid transit time of feed water into steam makes the generic AGR concept far more responsive, in principle, to demand changes [1]. Nevertheless, the AGR reactors would still face technical obstacles to load-following arising from Xenon poisoning, thermal stress and reactor instability (due to the use of enriched uranium fuel). These factors coupled with design specification (e.g. control systems), licensing formalities and only limited relevant operational experience explain the fact that AGR systems have not been used to follow load. Given that future strategies for the AGRs now look towards decommissioning, the possibility of life-extensions notwithstanding, there appears to be no reason to seek greater flexibility from these aging plants.

- Pressurized Water Reactors: E.g. Sizewell B, AP1000, EPR[5]

PWRs are the most widespread design in the world[6] and are inherently able to load-follow. Further reactivity control devices have also been implemented to improve transient performance, especially to deal with flux oscillations and to tackle power instability (arising from the higher core power density and the use of enriched fuel). Depending on the choice of these devices, the reactors are more or less able to follow load quickly. PWRs usually use soluble boric acid to offset xenon poisoning and fuel burn-up, and to change reactivity.

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[5] Advanced Passive reactor and European Pressurized water Reactor

[6] According to Nuclear Engineering International Handbook (2005), PWRs account for more than 60% of the reactors in use.

However, modern designs, such as the Westinghouse AP1000 mainly use control rod motion for load-follow manoeuvres. In France, where nuclear load-following is required to ensure supply-demand balance in a more than 80%[7] nuclear electricity system, some additional control rods have also been added to the usual design. As a result, reactivity control mainly consists of a smart management of three parameters: the reactor coolant temperature, the control rod assemblies and the boron concentration [5]. Special care is also needed to manage changes in xenon concentrations and hence both to ensure a uniform power distribution across the core and to monitor overall temperature effects [11]. Unlike the case of Gas Cooled Reactors, the relatively low coolant temperature range in PWRs (see table below) limits a plant's thermodynamic efficiency, its thermal stresses, and the fatigue of components.

Reactor	**Coolant Temperature range** (°C)
Magnox (Wylfa)	250-415
AGR (Torness)	335-635
PWR	Sizewell B: 294-325 EPR: 296-327
BWR	262-288
CANDU	250-295 ACR: 278-325
PBMR	500-900

Figure 2: Coolant temperature ranges for the main reactor designs (Source: Dr Parks, [1], [7], [13], [15]).

For many years, load-following requirements have been specified in standard terms of reference. For example, most PWR plants are capable to follow loads in a power range of 30-100% at rates from 1 to 3% per minute. Exceptional rates of 5% per minute or even 10% per minute are possible over limited ranges (Germany has particularly interesting load-following requirements [10]).

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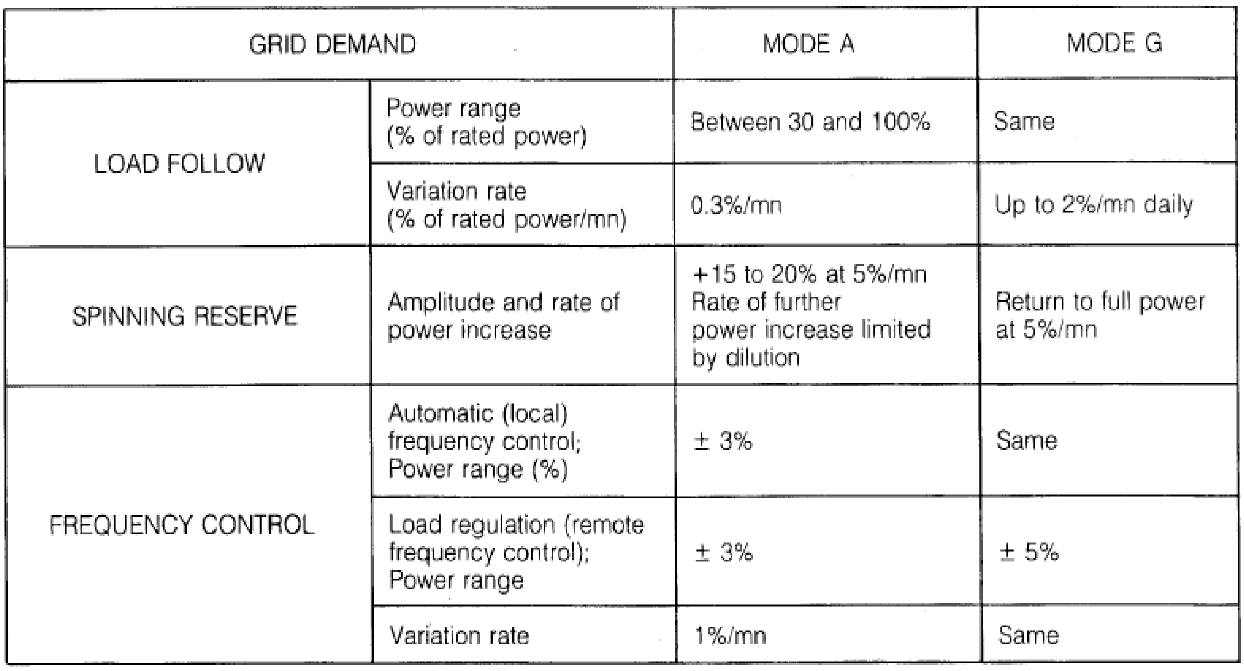
[7] 88% in January 2006, source: EDF

Looking to the future, further improvements of the Westinghouse Advanced Passive series designs (AP600 & AP1000) [12] and of the EPR [13] in respect of “grey” rods (“Mode G”), electro-mechanical equipment such as Reactor Advanced Manoeuvrability Package (RAMP) and in the case of the EPR a constant primary average temperature for power levels between 60 and 100%, ensure that flexibility will become a growing capability of nuclear power. The table below shows the improvements of the EPR’s load-following performance from mode A (mainly soluble boron use) to mode G (control rod use)[14]. Furthermore, Framatome’s intermediate operation “mode X” facilitates the mixed management of boron concentration and control rods and thus enables ever more operational flexibility [11].



GRID DEMAND		MODE A	MODE G
LOAD FOLLOW	Power range (% of rated power)	Between 30 and 100%	Same
	Variation rate (% of rated power/mn)	0.3%/mn	Up to 2%/mn daily
SPINNING RESERVE	Amplitude and rate of power increase	+15 to 20% at 5%/mn Rate of further power increase limited by dilution	Return to full power at 5%/mn
FREQUENCY CONTROL	Automatic (local) frequency control; Power range (%)	± 3%	Same
	Load regulation (remote frequency control); Power range	± 3%	± 5%
	Variation rate	1%/mn	Same

Figure 3: European Pressurized Water Reactor operating flexibility (Source: Framatome [3])

Given these significant improvements, one can therefore state that new build PWRs will offer operational flexibility as good as that of current fossil fuel plants [5].

- Heavy Water Reactors: The ACR[8]

ACRs have two features that can facilitate load-following. First, as with PWRs, the operating temperature range is only weakly coupled to output power, which helps limit the thermal stresses arising from power changes. Furthermore, CANDU reactors (of which the ACR is the

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[8] Advanced CANDU (CANada Deuterium Uranium) Reactor.

most modern version) have five control devices to ensure both flexibility and stability, especially through flux distribution control [7]. These are:

- Liquid-zone-control compartments (light water filled)
- Both adjuster and control rods
- Mechanically controlled absorbers
- Moderator poison (soluble B/Gd).
- Moderator level control (light water absorber)

As a result, HWRs are inherently very flexible and are able to load-follow between 60 and 100% of their full power. For instance, according to the International Atomic Energy Agency, the older “CANDU 6 plant can load-cycle on a daily basis.”[10].

- Pebble Bed Modular Reactor:

The “Generation III+” PBMR design is also expected to have excellent load-following capabilities, despite the high level of enrichment of the fuel. PBMRs have some other promising features, for instance, the reactor temperature at each point within the core remains at a constant high level (between approximately 500°C and 900°C, the inlet and outlet coolant temperatures) regardless of the load. Moreover, the flux distribution is relatively homogeneous. Generally in nuclear reactors problems of uneven flux distribution often greatly limit load-following possibilities. The PBMR power density is very low (about 6 MW/m^3). Furthermore, continuous reactivity control is achieved via “boosters” able to boost helium coolant pressure. This capability allows for quick load variations without excessive disturbance to the core flux distribution. Control rods (located in the reflector rather than the core itself) and absorber spheres are therefore only expected to be used for reactor shutdown [15].

In a UK context it is important to note that first and second generation reactor technologies from the 1950s to the 1980s were developed with no capacity to follow load. The most modern nuclear power plant in the UK, Sizewell B PWR, has undeveloped capabilities for flexibility. Looking ahead to candidate for new nuclear build in the UK all probable technologies have a technological capacity to follow load. The important point to recognise, therefore, is that almost whatever technologies are adopted for a nuclear renaissance the technical possibility for significant load following will arise. As such this directly contradicts the expectations of the British government quoted at the beginning of this paper. However, just because future nuclear power plants will be capable of flexibility, it does not follow that they will be operated in such a way. As we shall see the reason the nuclear power will continue to be a base-load technology are overwhelmingly economic rather than technical.

2 The management and economics of load-following:

The operating mode of a nuclear power plant is determined by demand needs and scientific, engineering, regulatory, contractual and economic factors. As nuclear power load-following remains a rather uncommon practice, exclusive to a handful of countries, economic information is larely unavailable. Most data on nuclear power plant economics assumes baseload operations.

It is widely known that for nuclear power, capital investment represents about 60% of the total levelised cost, Operations & Maintenance (O&M) around 20% and the fuel slightly less than 20%. A recent study carried out by the General Directorate for Energy and Raw Materials (DGEMP) of the French Ministry of the Economy, Finance and Industry [18], clearly shows the great differences in cost structure between nuclear power and fossil fuel generation (figure 4).

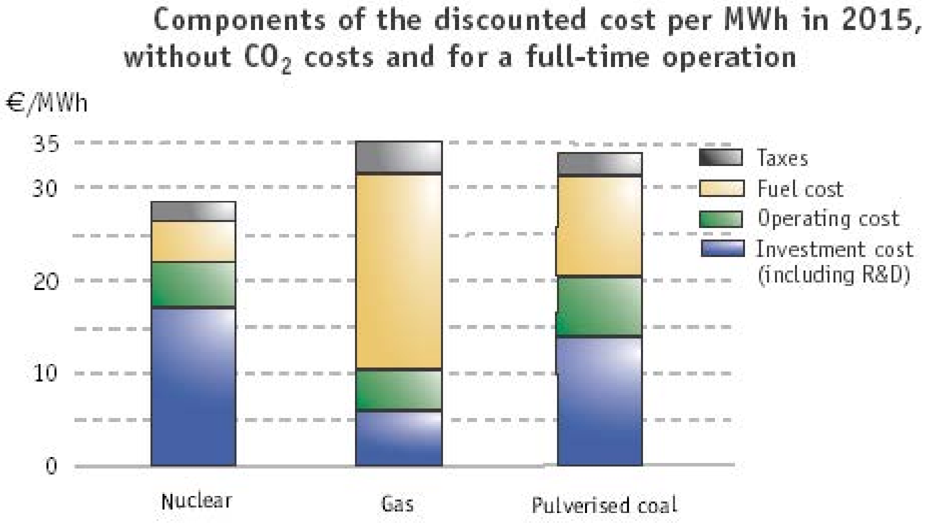

Figure 4: Components of the discounted cost per MWh in 2015 without CO_2 costs and for full-time operation (Source: DGEMP [18])

One must be aware that the figures greatly depend on the inherently uncertain assumptions (especially concerning discount rates, load factors, carbon and fuel prices)[9]. The relative competitiveness of nuclear power among generation options varies also from one country to another[10]. Despite such local differences, the cost structure of nuclear power always contains more fixed costs (especially capital costs) than fossil-fuel-based alternatives. This is the essential reason why baseload operation is generally preferred for nuclear power plants. We can safely, albeit perhaps somewhat simplistically, assume from a generating company's perspective, that, given the cost structure of nuclear power, operators would want their NPPs to operate at full-load for as much of the time as possible, in order to maximise income. Both capital costs and O&M are essentially fixed for nuclear power and the only variable cost (fuel burn-up) is of negligible overall importance. The simplicity in this view essentially lies in the implied assumption that all units of electricity produced are similarly remunerated. Another way of restating the same ideas is to say that from a market perspective, nuclear power has low fuel and low variable O&M costs. As a result, the marginal cost of NPPs (the cost to produce one more kWh when operating) is very low. Within the electricity market, nuclear is therefore at the bottom of the merit order and thus is "economically suitable" to operate at full-load. However, one must bear in mind that for all electricity generators, the cost of production of a MWh decreases with the level of plant utilization (see the figure below).

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[9] Please refer to the DGEMP report for the assumptions.

[10] Please refer to http://www.world-nuclear.org/info/inf02.htm or to recent studies by The University of Chicago (2004), the Massachusetts Institute of Technology (2003), or from British government organisations available via the website for the UK DTI Energy Review 2006 (http://www.dti.gov.uk/energy/review/page31995.html).

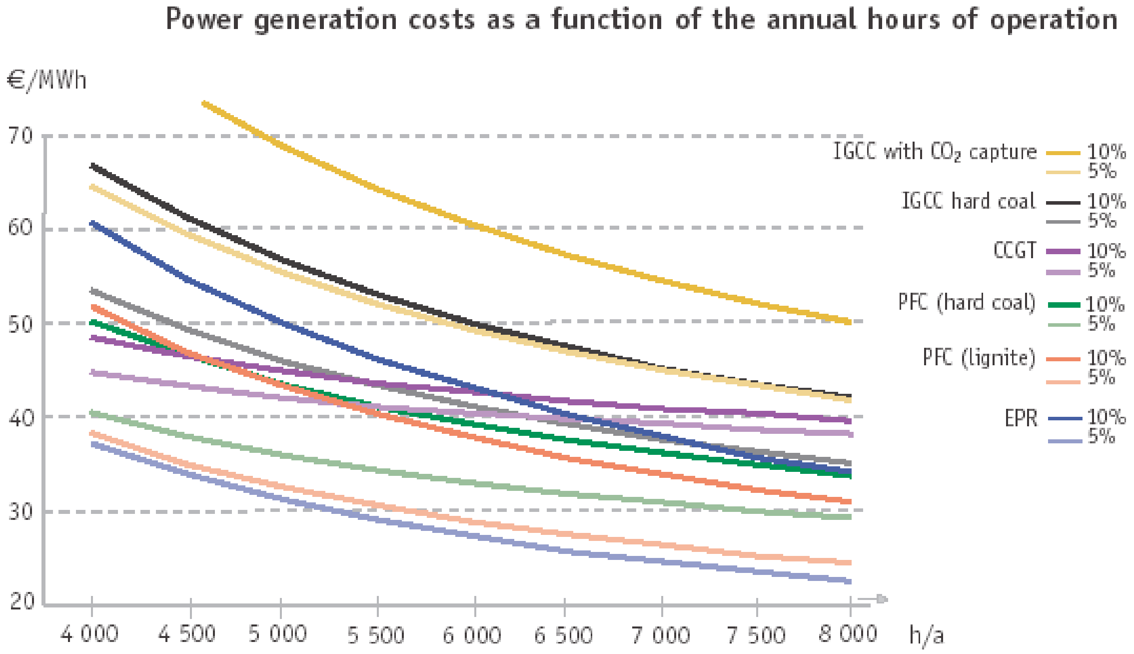


Figure 5: Power generation costs as a function of the annual hours of operation for 5% and 10% discount rates (Source: DGEMP [18])

Figures 4 and 5 provide insights into the range of relative competitiveness of nuclear power. Nuclear power becomes competitive above 5000 hours of operation a year, directly implying semi-base and base-load operations. These data, however, are limited in their usefulness by the fact that plant is assumed to be running at full capacity or not at all. Real load following operations (with smoothly varying outputs) in real electricity markets would represent a far more complex matter for which no data appears to be publicly available.

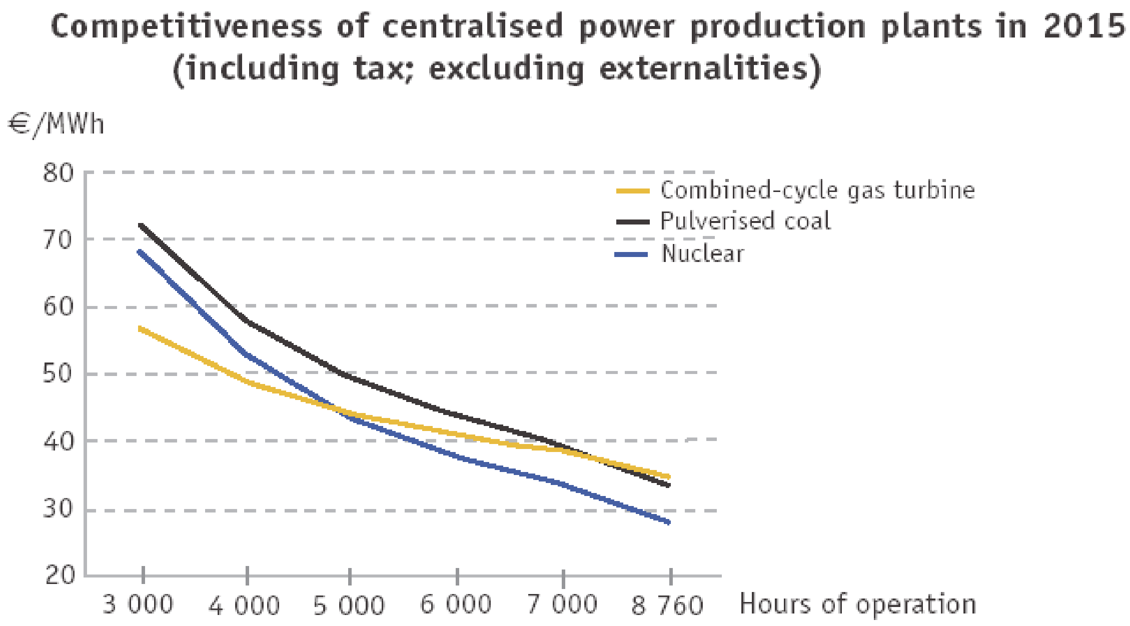
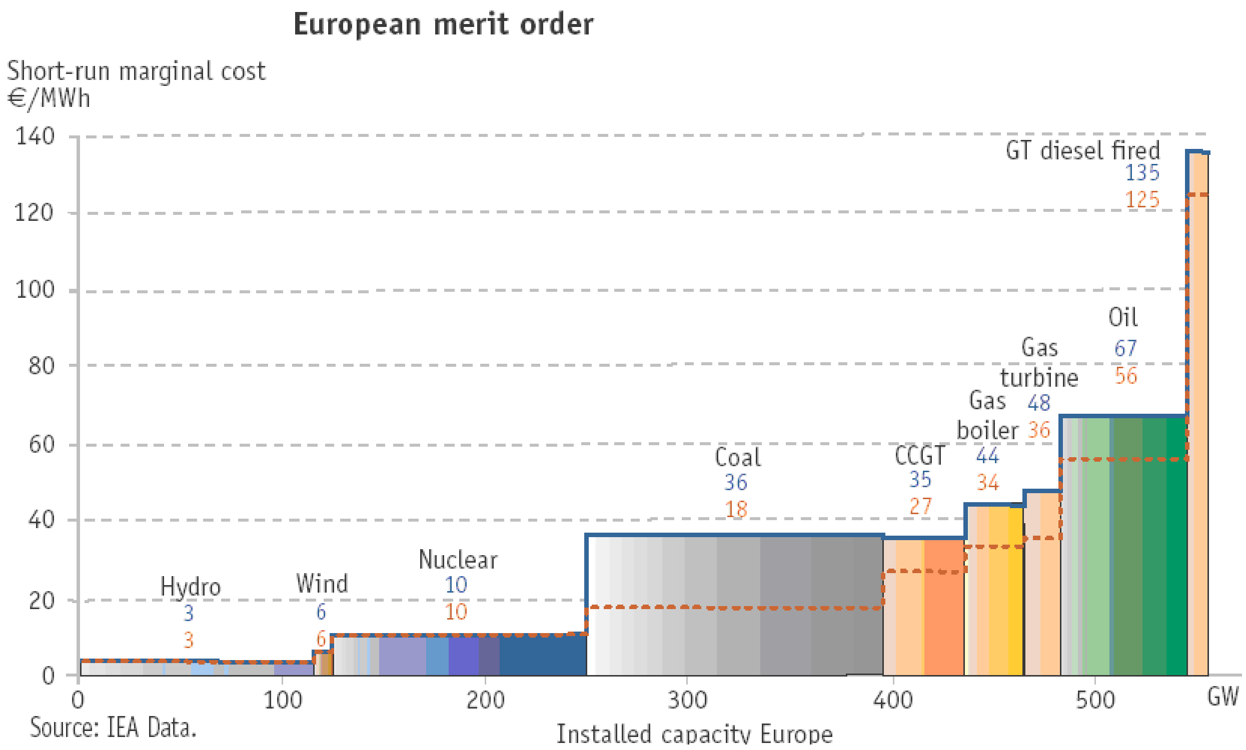


Figure 6: Competitiveness of centralised power production plants in 2015 (Source: DGEMP [18])

Once constructed, nuclear power plants have very low marginal costs, which hardly vary with the level of power output, therefore nuclear power plants will usually operate whatever the wholesale market price of electricity [19].

The majority of English and Welsh electricity is traded through bilateral forward contracts of a range of durations with generator self-dispatch, an alternative model (which operated previously in England and Wales and which was known as the 'Pool') is an electricity wholesale market with central-dispatch determined from an economic merit order [22]. In the latter structure (i.e. a "Pool" wholesale market) generators submit individual bids for half hour blocks in the following day to the system operator and the merit order is determined by their marginal costs. In such a market, the wholesale price for all electricity in that half-hour period is set by the marginal supplier, i.e. the lowest price of the last plant to meet the demand. In contrast the current English and Welsh arrangements imply that electricity despatched in a given half-hour slot can be rewarded with a wide range of wholesale prices determined by initially confidential bilateral contracts.

The short-run marginal costs of the main electricity generation sources in a single EU power market were calculated below by IEA showing clearly that in wholesale markets nuclear power is near the bottom of the merit order and favouring continuous base-load operations.


European merit order

Source: IEA Data.

Figure 7: European Merit Order[11] (Source: NEA/IEA [23])

In the current UK case of bilateral contracts the system operator has no direct role in determining the nuclear power plants to be despatched. All such major sources of electricity are governed by generator-supplier bilateral contracts, and, at present, all wind power is accepted by the system operator without constraint. Short-term supply-demand balance is managed by the system operator using spot market mechanisms not unlike those of the former pool. Prices in the balancing market can, however, be very generous, but they are insufficiently high to motivate flexible nuclear generation given its very high fixed costs discussed earlier. As the market evolves and new nuclear power plants come on-line it is not inconceivable that this situation could change and nuclear power might find a role in the balancing market and in “ancilliary services” [24]. The main services provided are: short-term or unscheduled load-following, frequency control and response, spinning reserve and reactive

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[11] The red dotted line shows the impact of carbon allowances [23].

power [24]. They can also be procured via both market arrangements and bilateral contracts [25].

The theoretical curve below illustrates the way market mechanisms dictate the plant utilization level [26].

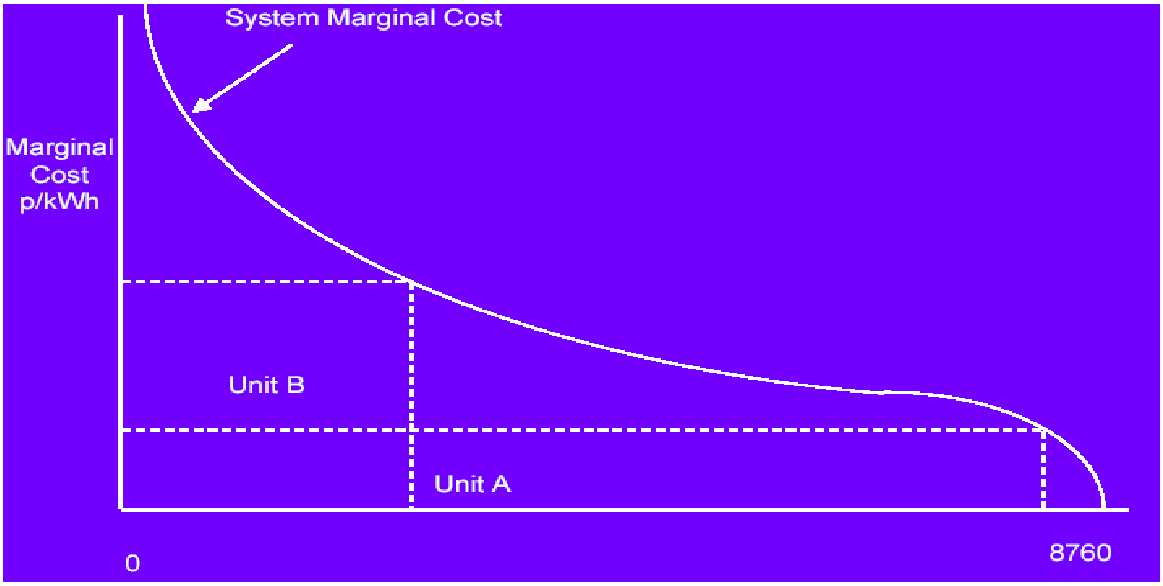

Figure 8: Cost duration curve sorted by marginal cost (Source: MIT [26])

However, the argument above is very much a story from the UK where nuclear power contributes roughly 20% of electricity. In France the situation is very different, for instance in 1983 France had the mix illustrated in figure 9 [12] [3]. In this interesting case we can see that French NPPs were indeed mainly operated as baseload, but even then several French PWRs had to operate at reduced-load about 10% of the time in order to ensure system balancing. Today, nuclear accounts for more than 80% of French electricity and, therefore, most NPPs have to often operate occasionally at part-load and some plants must be sufficiently flexible to load-follow to ensure grid stability.

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[12] With many thanks to Andrew Teller, Framatome ANP.

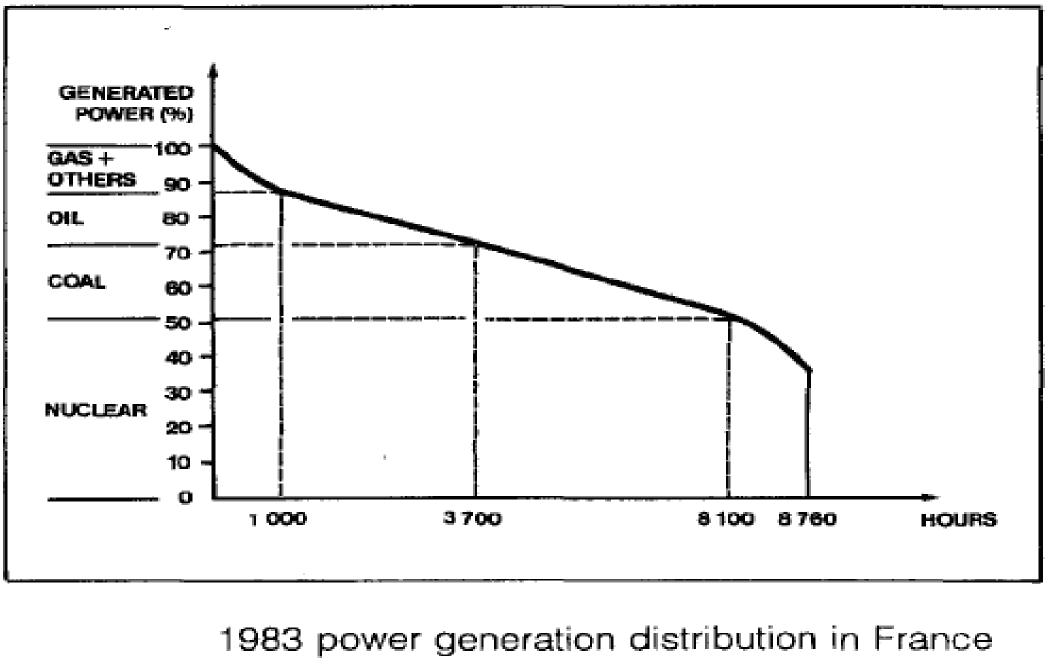

Figure 9: Power generation distribution in France in 1983 (Source: Framatome [3])

As a result, although the UK experience is of significant importance given its competitive energy markets (firm to firm and fuel to fuel) the economic context for flexible nuclear operations varies greatly from one country to another. For instance nuclear power’s contribution at the bottom of the merit order is even controversial; in 1998, studies in the US suggested that 40% of the NPPs could not even compete in the baseload end of the market [27].

As a conclusion, nuclear power is economically suitable to operate as a baseload generation because of its very low marginal cost. The basic market mechanisms therefore dictate its mode of operation and there is no incentive to load-follow with nuclear power. Oil, coal, and gas (closed and open cycle) are indeed better suited economically to load-following. However when, for historical reasons, a system has a very large proportion of nuclear power, NPPs must inevitably load-follow. In France for instance, most PWRs have to be able to change their output quickly if the French grid operator RTE asks them to, through its balancing mechanisms [29].

- For reasons which we trust are already clear, further investigation of the economics of nuclear load following force us to consider the French case where there is sufficient experience for reasonable inferences to be drawn, although, even in this case, data is limited.

As we have seen, the loss of income from electricity sales means it is more expensive to operate a NPP at part-load, but the variation of output may also produce increased costs. We said earlier that the marginal costs of extra part-load production could be small. It is important to note that this is in a context where lifetime levelised costs of electricity generation from nuclear power struggle to be competitive. While the marginal costs are low the fixed costs are high. If nuclear power coupled high fixed costs with high marginal costs it would indeed be uncompetitive. Care is required in preparing such cost estimates because secondary effects can arise; for instance, load-following operation may imply an increased use of soluble poison to control the reactor power. In such modes of operation much more water must then be treated and discharged, which might imply extra operating costs at the margin.

In France, NPPs have relatively low availability coefficient (about 80%) [30]. A recent study by EDF (Electricité de France) shows that operating NPPs at their maximum load improves their overall performance. It especially reduces the unscheduled outage coefficient from 3% to 1.8% in four years. This clearly suggests that load-following reduces the availability of NPPs, mainly because of more frequent maintenance (see below). The cost of such a difference of the unscheduled outage coefficient has been estimated at several millions euros [31]. More generally, some costs also arise from the maintenance and the lifetime issues. Load-following and frequency control indeed imply numerous and demanding manoeuvres, which increases the constraints on core equipment (please see Part 2 for further details). Some careful monitoring and maintenance are therefore needed to ensure reactor safety. Control rod mechanisms, temperature and pressure fluctuations especially need to be monitored [3]. Even if this induces higher maintenance costs, it is difficult to estimate the costs implied by R&D developments, extra monitoring systems, more frequent maintenance and potentially increased outages. No study has yet been undertaken by the French authorities to estimate these costs.

Moreover, one can indeed assume that because of frequent load-following cycles, thermal stresses, fatigue and mechanical constraints, flexible NPPs are likely to age quicker than those operating at base-load. This reduction in NPPs' lifetime is economically crucial and implies indirect costs of millions of euros [32]. However, according to Framatome ANP, EDF and the French regulatory authority, there is today no clear evidence that load-following will accelerate the ageing of NPPs. Even if they concede that a very small number of pieces of equipment (control rods drives for instance) may be adversely affected, they still argue that proper designs and load-following procedures ensure the core components are not excessively degraded. Also, there is the possibility that EDF might concentrate load-following operations on just a few NPPs, in an almost sacrificial manner so as to avoid damaging the wider NPP fleet [32]. Even if nuclear power flexibility may be more costly, one should bear in mind that it may also create great opportunities, especially in terms of system management.

As France moves towards more competitive energy markets, operational flexibility is considered as a high value product and may be required even more often. In this new context, flexible NPPs could then have both stability, as a constant source of revenue, and a relative flexibility to meet system needs, which could make them very attractive within an operator's portfolio [21]. A more flexible operational management can indeed create great opportunities.

To illustrate the benefits of flexible nuclear power, one can consider the German electricity system. One must first keep in mind that wind power is at the bottom of the merit order (see figure 10) but is not dispatchable. In Germany, it accounts for a significant fraction of the electricity generation and is allowed to operate at all times (as a consequence of the German "Feed-in law"). As a result, each installed MWh of wind requires some flexible capacity reserve. This is potentially a great opportunity for flexible NPPs, as they may be paid significantly more to operate at reduced load[13], although one must concede that the problems of intermittent wind power are frequently exaggerated by those proposing an expansion of nuclear power generation. Nevertheless there would appear to be economic opportunities for NPPs to be used as flexible reserve capacity for intermittent renewables [33].

In countries with a long history of PWR based nuclear generation, load-following capabilities might also allow old and less competitive NPPs to be operated as load-following generation.

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[13] With thanks to David Ward (Magnox Electric).

When it happens that, due to higher marginal cost, some NPPs are higher in the merit order, it is indeed economically more appropriate to load-follow (see above).

In France, another motivation for flexible nuclear power plant operations is widely used: when demand is low, EdF selects a few NPPs only to provide for large power variations and to load-follow in so doing some costs may be increased, but fuel burn-up is reduced. In this way EdF can defer reactor refuelling to times when it is most convenient [5]. A PWR cannot be refuelled while operating. The refuelling is a complex task requiring several weeks of shut-down. Sizewell B in the UK is refuelled every 18 months in either the spring or autumn[14]. In this way a winter refuelling shutdown is always avoided, when wholesale power prices are highest. Such smart management is decisive as it increases plant availability and thus ensures cheaper electricity generation during high demand periods. Moreover, system operators postpone grid constraints and outage costs. Flexibility of refuelling is surely a most attractive opportunity. CANDU heavy water moderated reactors operate with on-power refuelling with several fuel replacements occurring most daily [34]. As there is no requirement for a lengthy refuelling shutdown every eighteen months load factors for CANDU plant can be very high and long-term operational flexibility is optimised.

Another method by which NPPs might operate close to the top of the merit order in a given country is to shed surplus nuclear electricity via sales to neighbouring electricity systems. France is a major exporter of nuclear-generated electricity and it would be interesting to study the relationship between electricity exports and NPP operations. Such considerations lie beyond the scope of this paper.

Conclusions:

To answer fully the question “is nuclear power flexible?” one must first appreciate that NPPs are part of a complex electricity system and that these systems differ technically and economically from country to country.

Somewhat simplistically we have separated the issues into the technical and the economic. Old British reactors (e.g. Magnox, AGRs) were neither designed, nor expected, to load-follow.

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[14] With thanks to British Energy for this information

However, more recent designs such as PWRs, CANDUs and PBMR reactors are indeed flexible and they all have very good technical capacities for load-following.

We have considered cost structures, and conclude that nuclear power has a very low marginal cost. As a result, at the time of deployment into vertically-integrated monopoly electricity systems nuclear power plants were placed at the bottom of the merit order by system operators. In "Pool" style spot markets NPPs would bid in at very low prices to ensure despatch and payment at the market clearing price. In the current English and Welsh market most electricity is traded via medium and long-term contracts and, as such, notions of merit order (either in an administrative or a market-clearing sense) are somewhat blurred. Nevertheless it is still the case that in today's liberalised British market NPPs operate in a base-load capacity. In the British case only Sizewell B NPP has any regulatory and technical capacity to load follow. The very limited participation of Sizewell B today in non-baseload operations implies that, even with a next generation reactor fleet providing roughly 20% of UK capacity, this capacity would only be operated in a base-load mode irrespective of regulatory and technical opportunities to do otherwise. The French situation, however, reveals that the UK situation is not the only model of relevance. France is distinct from the UK because of its slow pace of market liberalisation and unbundling and also for the far higher contribution of nuclear power to national electricity generation.

If the UK is to move to decarbonise its electricity system by 2050 then its seems possible that the UK might greatly increase nuclear power generation forcing a reassessment of operational modes for plants closer to the margin. In addition, strategy within the UK electricity industry might alter in the future as result of continental European nuclear power plant operators entering the UK market. It seems probable that load following will be kept under review by many parties in the years to come. This paper is merely a first step.

Frankly, in the UK context, nuclear power has been and is likely to remain a baseload-only technology for economic reasons, even as the technical reasons fall away. However, in the controversial and topical nuclear debate, it is our intent that this paper, as well as the Energy Consultation Review, will help make decision-makers aware of the technical flexibility of modern NPPs and the reasons why they will, or will not, operate only at the bottom of the merit order in future.

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