



For economic reasons, Nuclear Power Plants (NPPs) are usually operated to provide base load power, i.e. to operate constantly at maximum or close to maximum output. Contrary to the widespread impression that large-scale nuclear power stations are inflexible, NPPs are in many cases technically able to serve the demand of load following (LF) operation as well as frequency control of the transmission grid, which is particularly useful and necessary in countries with a high share of renewable power generation. LF operation has been performed in Germany and France (and other countries outside of Europe, for example the US) for several decades now [1], subject always full safety assessment and the approval of the national safety regulator.

# Nuclear Energy Factsheets

## Load following capabilities of Nuclear Power Plants

### • Load following in current Nuclear Power Plants

We can distinguish three different types of flexible operation for NPPs:

- Frequency responsive operation, where the plant is set to operate at less than full load, and its output varies automatically in response to changes in the system frequency.
- Profile operation in which the operator offers periodic load changes to create a profile which varies across the day (typically this involves "two shifting" over a 24-hour period with reduced output overnight).
- Load following, where the operator is instructed by the system operator to carry out manoeuvres at short notice to change the output in accordance with changing system requirements.

The main parameters for a NPP in regard to the LF capacity are as follows: power gradient (rate of change in power), power increment (amount of power change) and minimum power output [2].

Reducing power output of a NPP is always possible in a timely manner independent of type [2]. Although the achievable power gradient of Pressurised Water Reactors (PWR) and Boiling Water Reactors (BWR) for altering output is similar, the technical operation to perform immediate load changes is different. The general scheme of a PWR and a BWR is shown in Figure 1 and Figure 2.

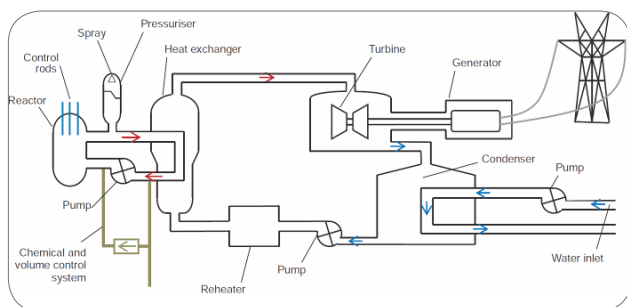


Figure 1: General scheme of a PWR [3]

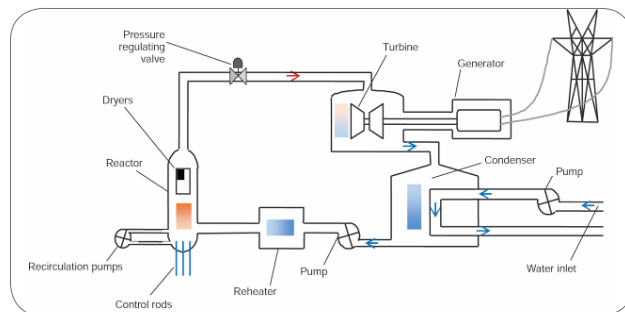


Figure 2: General scheme of a BWR [3]

A load change of the PWR is mainly performed by means of the control rods to achieve the required thermal reactor power. Fine adjustment of the reactivity within the reactor core is performed by controlling the boric acid concentration within the primary water circuit [2], [4]. The coolant temperature stays constant in the range of 60-100% load and thus reduces thermal stress [2].

The power output of a BWR can either be controlled by means of the control rods below 60% of the NPP's design load or by means of change of coolant water flow rate (change of power input of the recirculation pumps) in a range of 60 to 100% load. Adapting the flow rate through the reactor core affects the moderation and therewith the reactivity [2]. This is the preferred method for LF as it does not stress the fuel rods, and power distribution in the core stays almost constant [5]. A BWR can change its power output faster than a PWR in the upper load range. For both types, temperature and pressure remain constant in the main steam system [2].

The Generation II NPPs in Germany are designed to change their power output by up to 10% of their nominal capacity per minute; common practice is 2.5% to 5% of PN/min [6]. Considering the German NPP capacity in operation prior to 2011 of about 20.5 GW from 17 reactors, about 10 GW of regulating power could have been provided by NPPs within 15 minutes [7]. For the eight remaining operating reactors with a net capacity of around 10.6 GW the LF ability can be assumed to be 5.3 GW – available within 15 minutes with a load gradient of 5 %/min for a reduction up to 50% load for each NPP (refer to Figure 3).

In France comparable power gradient values of 5 %PN/min for the range of 30-100% [2] and +/- 2.5% for short-term frequency modulation (few seconds) are given [8]. Due to the high dependency of the French electricity supply on nuclear power (about 75%) this is a necessity, as NPPs have to be suited for overnight and weekend load following and for complete interruptions for short periods of time (hours to days) [8].

In addition to Germany and France, Belgium, Finland, Switzerland and Hungary are also practicing either load following, power modulation or grid frequency stabilisation at their NPPs to different extents. The need for NPPs to load follow depends on the national or regional energy mix: in Scandinavian countries, for example, where there is a large share of hydro, or in countries where there is still a large share of fossil-fired generation, balancing intermittent renewable output can usually be performed more economically by modulating the non-nuclear components of the mix.

Without going into detail, the following optimisation potentials for the LF capability of Generation II NPP have been identified in [2]:

- fuel management strategy optimised for LF operation
- optimised control rod manoeuvring
- look-ahead NPP operation

### • Comparison of NPPs with other conventional PPs

A comparison of the ability of German NPPs versus newly-built hard coal and Combined Cycle Gas Turbine (CCGT) PP to run in load follow mode to handle intermittent loads between 50% and 100% nominal power is illustrated in Figure 3.

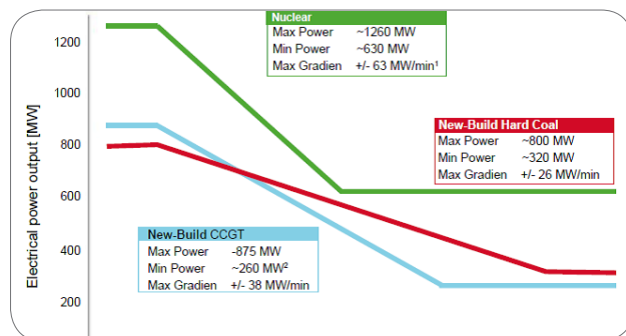


Figure 3: Comparison of load follow ability of NPP, Hard Coal PP and CCGT [8]

As shown in Figure 3, the time ranges, over which the load gradient can be driven, are similar. A NPP can provide 630 MW within 10 minutes, a hard coal PP 480 MW within 12 minutes and a CCGT around 500 MW within 21 minutes. This results in maximum power gradients of 63 MW/min, 26 MW/min and 38 MW/min respectively. "Thus not only nuclear can run in load follow mode, but it can be better than coal and CCGT" [8].

As Figure 3 indicates, NPPs can compete with conventional fossil power generation with regard to LF operation.

To summarise these findings, we can say that NPPs can compare well with other conventional PPs in the matter of flexibility. With respect to power gradient and power range, NPPs even outclass other conventional PP technologies, such as hard coal or CCGT, due to their large unit size and technical characteristics. The LF capability was already considered as a design criterion of German and French NPPs [4]. Conditions for the two countries were quite similar, as Germany originally planned (in the 1970s) to increase its total nuclear share in generation to about 70%, which would be comparable to the situation in France today [4].

### • Safety

The safety of a NPP operating in LF mode is a paramount consideration and has to be assured. Not all nuclear plants are suitable for providing flexibility, and detailed work is needed to assess the impact of changes to the operating mode to ensure that the safe operating envelope is not compromised and that the impact of load following is fully assessed and approved by the national safety regulator. Most plants have been operated in base load, since there was no requirement for LF operation. Some plants have however been operated routinely in LF operation mode in the past decades [4]. Extensive operating experiences are available for load changes with power gradients of up to 2% / min and power increments in the range between about 50 to 100%, with some experience also of higher gradients. Ludwig et al. argued that the safety of NPPs is not affected by LF operations. All relevant plant states were covered in the safety cases of the plants. Continuous monitoring of fatigue of exposed plant components, in particular of fuel rods, which are the most stressed by LF, is assured by periodic inspections of safety-related components. Considering the further expansion of renewable energies, the LF operation of NPPs will be increasingly necessary [2].

### • Abbreviations

Abbreviation	Description
BWR	Boiling Water Reactor
CCGT	Combined Cycle Gas Turbine
EPR	European Pressurised Reactor
IAEA	International Atomic Energy Agency
LF	Load Following
NPP	Nuclear Power Plant(s)
PP	Power Plant
PWR	Pressurised Water Reactor
R&D	Research and Development

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