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Increasing Needs and Solutions for Non-Baseload Operation of Nuclear Power Plants

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ABSTRACT

Operation at steady full power, i.e. baseload operation, of nuclear power plants (NPPs) is usually considered to be the most efficient use of capital investment. Therefore, design and operation of most existing nuclear power plants (NPPs) are optimised to operate in baseload mode. Recently, there is an increasing need to operate NPPs in non-baseload mode, specifically performing frequency control and load following. These needs are typically due to a large nuclear generating capacity, increasing share of renewable generation, deregulation or evolution of the electricity supply systems and markets. Re-optimization of NPP design and operation for non-baseload (flexible) mode of operation necessitates operational, economic and financial rearrangements to maintain the capital investment, in addition the adaptation of technical and regulatory changes. This paper discusses the aspects of design or operation of NPPs in flexible mode based on the existing knowledge and experience and it is primarily based on the recent study that was prepared by the International Atomic Energy Agency (IAEA).

Keywords: *non-baseload, load following, frequency control, flexible operation*

1 INTRODUCTION

In absence of a direct and economical storage of electrical energy on a large scale, the electrical generation is currently adjusted to closely match electrical demand continuously. The main reason for this balancing is to maintain a stable system frequency since a mismatch between the generation and demand will increase or decrease the system frequency. Although this balancing may be partially achieved by several methods on the demand side, i.e. to encourage electricity consumers to alter their electrical usage from periods of high electrical demand to periods of low electrical demand, balancing of the electrical system mainly controlled by the management of generation. This is achieved by changing the electrical output of some individual generating units to stabilize system frequency, as well as to control power flows on the transmission system. Usually, the grid system operator manages the balancing of demand and generation and requests electrical output adjustments from the individual generation units. Need and performance of increasing or decreasing the electrical generation by individual generation units varies depending on the grid needs, demand variations, generation mix and commercial or regulatory arrangements. Changing the electrical output may be needed and to be performed rapidly, i.e. within seconds, or slowly, within timescales of minutes or hours. This output change can occur several times a day or a few times in several years. Furthermore, the generating units utilizing various fuel sources are requested to change output, customarily, in a commercial/financial merit order to minimize overall operating costs while providing the benefit of grid system stability. As such, the generating units with lower marginal cost are operated at full power as much as possible, i.e. in baseload mode, while higher marginal cost (typically corresponding to higher fuel costs) units reduce or cease output, e.g. at times of low electrical demand, or operated at partial load to be able to change output when requested by the grid system operator, i.e. operate flexibly.

Herein, the term 'flexible operation' (or 'operating flexibly') is used interchangeably with 'non-baseload operation' to describe any mode of operation of a generating unit that is not 'baseload' as defined by the IAEA publication [1] and the specific focus in the following discussions are on changing electrical output to match generation with electrical demand on the electricity grid system (Fig. 1) in NPPs.

Since NPPs have relatively low fuel cost (low marginal cost), nuclear generating units are preferred to operate as baseload generation units except when it is necessary to reduce power or shutdown due to the plant specific needs, i.e. for maintenance, refuelling or for other operational or safety reasons. In the early years, a number of countries/utilities considered and requested NPPs with flexible operation capabilities. Some also carried out some flexible operations such as a limited amount of load following [2–6]. Nevertheless, since that time, the majority of NPPs have been baseload generation units and their plant systems, procedures and equipment have been optimized for operation in that mode. However, due to several reasons, there is an increasing need to operate nuclear units in non-baseload mode. More specifically, NPPs are being considered to perform frequency control and load following. These needs are typically due to (or as a result of combined impact of) a large nuclear generating capacity, increasing share of renewable generation, deregulation or evolution of the electricity supply system and the market. This increased the consideration for operating NPPs in flexible mode.

The decision on whether — all or some of — the NPPs should operate in a flexible or baseload mode requires an understanding of the grid system needs. Subsequently, thorough investigation of several factors which would impact all stakeholders who should agree on the feasibility of flexible operations of particular NPPs should be evaluated. Within the electricity market framework, the impact from flexible operation of NPPs and associated needs have to be well understood with respect to the efficient use of capital investment and the impacts need to be minimized, eliminated or compensated for serving the overall energy structure needs while preserving the nuclear safety.

Technically, the planning and design of a new built NPP should have usually had flexible operations in mind and these capabilities need to be validated during commissioning with any limitations should be determined at the beginning of operations. The NPPs that have previously operated only in a baseload mode, and are now converting to non-baseload mode, similar considerations should be given and solution for design and operational changes should be developed. Substantial plant modifications may be needed to support flexible operations, depending on the existing design capabilities and the extent of flexibility requirements. In either case, the operating license application (safety case) would be developed to support flexible operations and existing operation and maintenance strategies may need adjustments.

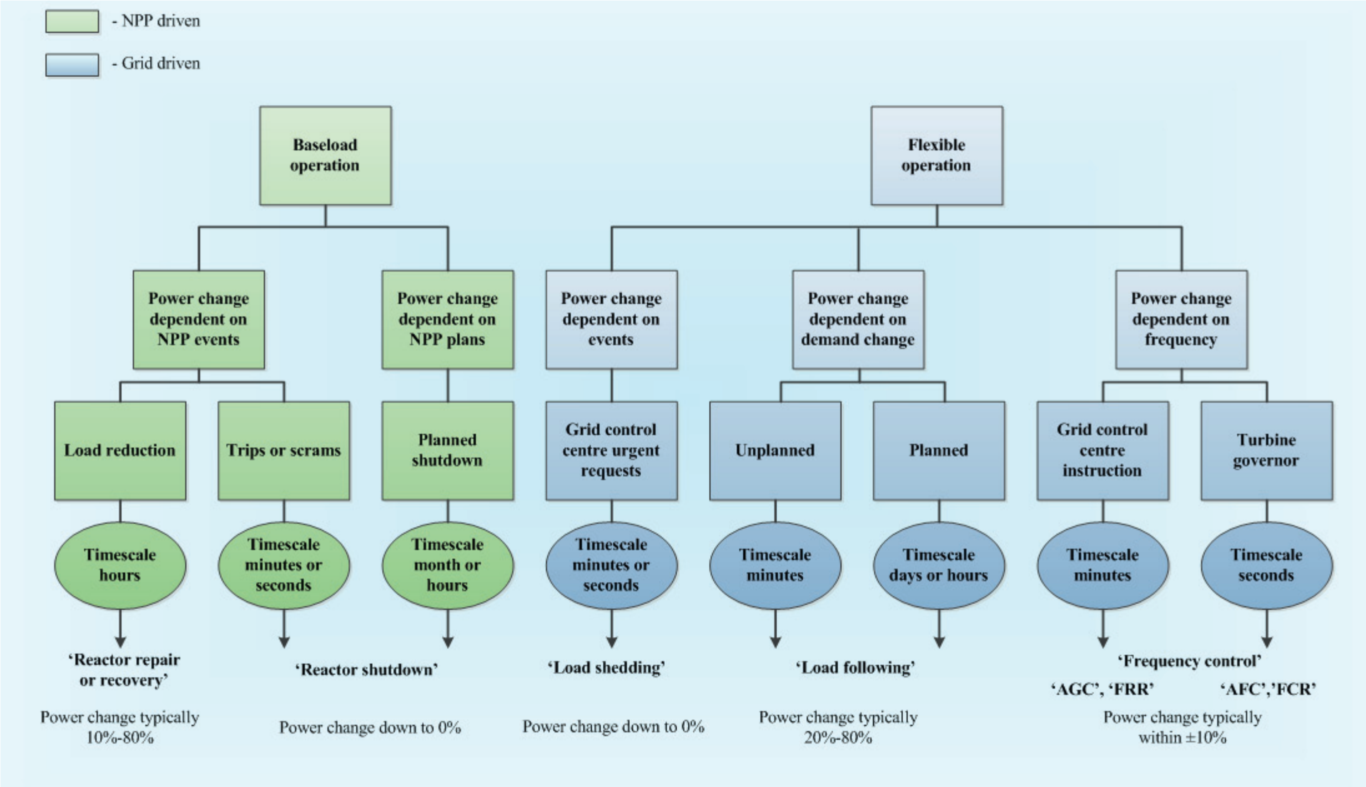

Figure 1: Definition of Load Changes under Baseload and Flexible Operations [1].

2 REASONS FOR FLEXIBLE OPERATION OF A NPP

If the total electrical generation capacity of the NPPs in a grid system is a small percentage of total capacity; and, it is significantly less than the minimum residual demand, there would be little or no need for NPPs to operate flexibly. It should be noted, however, that this is a general rule and particular grid systems may have some other specific needs and requirements to balance generation with demand. "The definition of 'small fraction' and 'significantly less' depends on the structure, conditions and control methods of the grid system" [1].

Moreover, it will become necessary for NPPs to operate flexibly in order to control system frequency and power flows, if:

- Nuclear share in the total electric generation capacity is large;
- NPP generation is too large on a small grid system;
- There is a significant share of intermittent or non-dispatchable generation;
- Transmission system has constraints;
- There are limitations and constraints on non-nuclear generators legislatively and/or within market regulations.

The reason for NPPs to consider and implement flexible operations can be based on one or more of these conditions.

2.1 Nuclear share in the total generation/nuclear output scale on a grid size

If the total capacity of nuclear generation is near or above the minimum electricity demand in a grid system, it will challenge the grid system operator in matching generation with demand — or maintain adequate reserves utilizing only the non-nuclear generation. This will not be particularly possible during periods of low electricity demand. In such cases, flexible operation of NPPs will be needed and they would be requested to reduce output to contribute to frequency control at times of the minimum demand. This condition is not necessarily limited to overall percentage of generation in a country scale and it may be applicable in regional networks or may extend to networks international level. For example, NPP(s) may contribute a large percentage of generation in one region of a country, even though the nuclear generation is a small percentage in the whole country. This may be particularly applicable and significant if grid connection of that particular region with large nuclear generation to the rest of the country is weak. On the other way around, there may be no need for NPPs to operate flexibly if a country (or region) is connected strongly to a large network, although the share of nuclear generation is very large.

Also, NPPs are typically large, if not the largest, generators unit on many grid systems. This is especially the case in the countries connecting their first NPP to the grid (newcomer countries) considering the available NPP designs currently. For such cases, the effect of an unplanned trip of large NPP on the system frequency can be problematic in order to avoid a system blackout, if the output of that generating unit is more than about 10 per cent of the system demand at the time [5]. Therefore, operating the new NPP flexibly may be needed, e.g. reducing electrical output and/or thermal power whenever demand on the electricity system is low.

It should be noted here, as stated in Reference [1], that: "system frequency is generally more variable on small electricity systems than on large interconnected networks. Therefore, for a country that is installing its first NPP on a relatively small system, the NPP can greatly improve the stability of system frequency while it is operating if it is able to provide good AFC".

2.2 Share of intermittent or non-dispatchable generation

Lately, a significant growth in renewable generation, particularly from wind and solar energy sources, has been observed in many countries, specifically due to the carbon emissions strategies in order to meet government policies. Although these generators, such as wind turbines or solar systems have zero fuel cost and usually have priority status in government regulations and requirements, they have intermittent and variable output. Therefore, increasing share of renewables created a need for NPPs in a grid system to start operating flexibly including the following aspects:

- Output of renewable generation units vary largely with limited predictability and is not always aligned with variations in demand;
- Renewable generation units are not readily dispatchable;
- Renewable generation units are replacing conventional generation sources, such as coal fuelled plants that usually provided reserve. This necessitates NPPs to reduce power during times of low demand and/or high renewable generation output on top of increasing the amount of reserve that is required;
- Large wind turbines and solar panels do not directly provide inertia to the grid system. Consequently, growth in those — displacing turbine-generators — will reduce the system inertia resulting in a significant need for more generating units, including NPPs, to be able to respond more quickly to changes in frequency, i.e. to operate in automatic frequency control (AFC) mode.

Therefore, there is a growing need for NPPs to start operating flexibly because of increase in variable renewable generation. As a general rule, if the minimum residual demand falls to a level that approaches the installed nuclear capacity, or if the system inertia falls too low, flexible operation of NPPs is needed [1].

2.3 Constraints by transmission system and/or on non-nuclear plants

A limited capacity of the transmission network may restrict NPP(s) to operate at full rated thermal power (RTP) or at rated electrical output (REO) under some grid system load including periods of transmission circuit outages. This may well be the case, for example, when additional generation sources are connected near the NPP without improving the transmission network accordingly.

A low degree of interconnectivity between neighbouring power systems can also force NPPs to participate in provision of required flexibility when energy demand significantly fluctuates. As mentioned earlier, strong interconnectivity with neighbouring power systems may reduce the need for a NPP to operate flexibly to allow the required power flows across the interconnection. Conversely, flexible operation of NPP may reduce transmission constraints.

Also, environmental legislation in some countries puts restrictions on operation of non-nuclear power plants, e.g. coal-, lignite-fuelled units for emission, or hydroelectric plants for maintaining for conservation of fish stocks, irrigation or flood control. This may affect the ability of such plants to remain within the environmental limits when operating at part load, or to change output rapidly or frequently. For example, a gas-fired plant may exceed the NO_X limits below 60 per cent RTP. The legislation that — due to being economically unfeasible — result in the retirement of older fossil-fuelled plants that previously provided flexibility also may increase the need for NPPs to operate flexibly to replace their contribution in balancing and providing reserves.

Market deregulation also restricts the manner of operation in many countries or regions. For example, if the market is deregulated and the technical or commercial rules require all generating units to have at least a defined minimum capability to operate flexibly, this requirement will apply to NPPs even if there is rarely a need for them to operate flexibly.

3 FEASIBILITY EVALUATION AND DECISION ON FLEXIBLE OPERATIONS OF A NPP

The decision on flexible operation of a NPP is driven by a business case based on the necessity or the probability to have to periodically reduce the thermal/electrical output of the NPP during its operational lifetime, due to aforementioned commercial or grid operational reasons. Framework of energy policies and technical, economical and legal regulations or market incentives also have to be considered in preparation of the business case.

A typical feasibility study by the NPP owner/operator organization on identification of technical, financial or operational impacts is illustrated in Fig. 2.

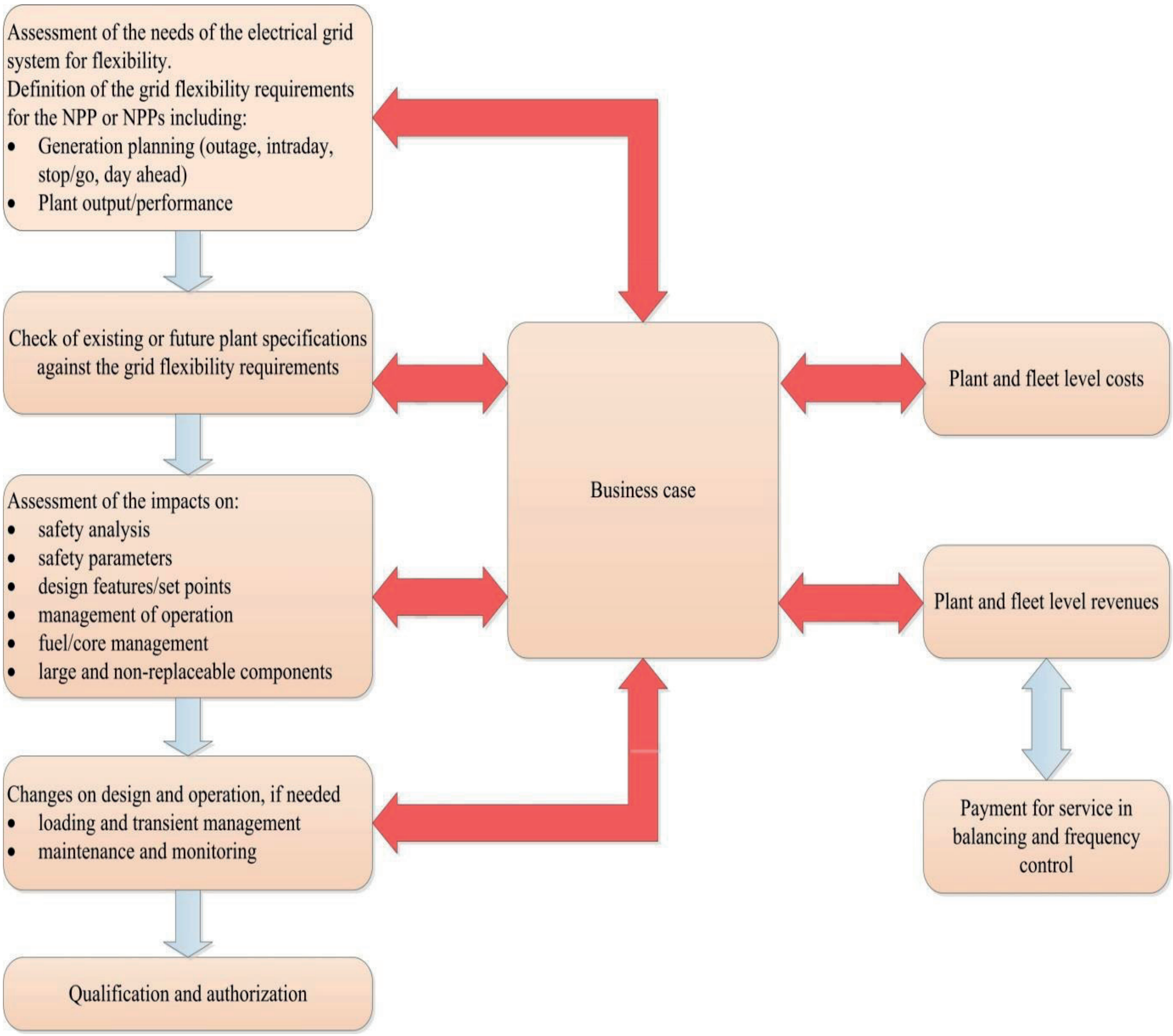

Figure 2: A Simplified Process by NPP Owner/Operating Organization in Making Flexible Operation Decision [1].

Such study is part of a decision making by integrating the impacts, associated costs-benefits including the potential payments for providing balancing services, overall energy policy and legal and regulatory aspects, etc. This fundamental process by the NPP owner/operator organization for deciding on whether to operate flexibly should cover the key aspects in deciding on the desired extent and form of NPP flexible operations. It should also be noted that the decision has many stake holders in addition to the NPP owner/operating organization (Fig. 3).

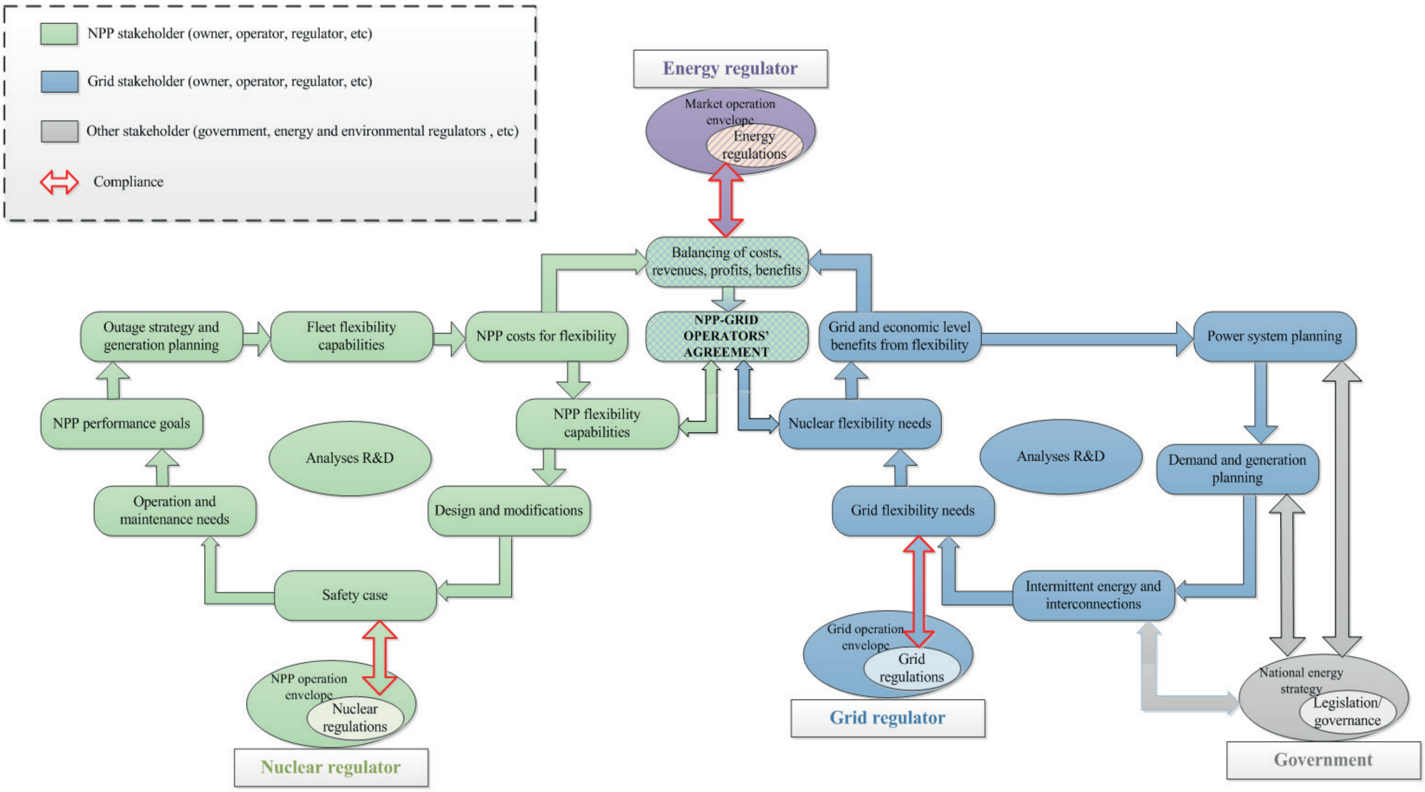

Figure 3: Interfaces in Flexible Operation Decision Making Activities [1].

4 ASPECTS OF FLEXIBLE OPERATION IMPLEMENTATION

A complete understanding and evaluation of a NPP's existing design and licensing basis and operational strategies, as well as the future state of those during the flexible operations, is necessary for making an informed and effective decision on the need for, and extent of, flexible operations. Knowing the current plant capabilities and operational strategies will confirm the capacity and capability for flexible operations and will support planning and implementation of new design features or modifications to achieve future capabilities. More importantly, it will ensure that the NPP will perform flexible operations safely, reliably and efficiently. Therefore, this evaluation includes a complete review of not only the design, operation and maintenance specification of NPP's system, structures and components (SSCs), but also the design and safety analyses, operational limits and conditions (OLCs), applicable regulations, codes and standards, operating procedures, training and qualification of personnel. The scope and extent of this evaluation varies for each individual NPP since it depends on many variables such as technology, design, operating experience, regulatory conditions, and of course, the magnitude, rate and periodicity of flexibility required.

Some countries, such as France and Germany have already designed (or modified) and have operated their NPPs flexibly collecting many reactor-years of experience and knowledge of flexible operation. This experience and knowledge provide a valuable resource in understanding the requirements, needs, challenges, solutions, and lessons learned. In addition to the French and German operational experience, various studies [7–13] investigated the feasibility of NPP flexible operation. The IAEA study [1], which collected this information in order to disseminate to IAEA Member States, organized impacts and solutions into four areas based on the aspects of impacts:

- Analysis based aspects;
- Phenomenon based aspects;
- Component based aspects;
- Human performance based aspects.

Table 1 illustrates a subset of impacts discussed in the IAEA study, namely the interface of the phenomenon and component based aspects on the reactor core and associated systems.

Table 1: Flexible Operations Impact on Reactor Core and Associated Systems [1].

Component / Phenomenon	Fuel rod	Fuel assembly (and fuel channel for BWR)	Control rods	Control rod drive mechanism	Core detectors	Core shroud
Fatigue	X	X	X	X		X
Erosion/corrosion	X					
Wear and tear			X	X		
Core power redistribution	X				X	
Pellet-to-clad interaction	X					
Creep induced channel distortion	X	X				
Extended operating cycle	X	X	X	X		
Chemical impurities	X	X				
Ageing			X	X		

5 CONCLUSIONS

In several countries, flexible operations have been a daily operational reality for many years with full compliance and conformance with safety, quality and reliability requirements while managing the efficiency and financial impacts of such operation. Additionally, in many countries who have not had their NPPs operating flexibly, assessment and evaluations of the electricity system and associated energy plans and strategies have been performed and decision have been made for the current or future NPPs to operate flexibly. Therefore, it has been feasible to design a new NPP, or convert an existing NPP, for flexible operation with safety, reliability and quality.

Primary consideration for flexible operation is matching the flexibility needs of the grid system and the capabilities of NPPs for flexible operations. Therefore, the owner/operators of the NPP and the grid have to understand and agree to a feasible solution that would satisfy needs and capabilities.

As the nuclear safety is overriding priority, it is also necessary to communicate with nuclear regulatory body (and the grid regulators) during the process to inform and obtain guidance for an effective regulatory and operational decision making framework for safety.

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