

WNA Report

Optimized Capacity: Global Trends and Issues

2012 edition

A Report by the World Nuclear Association's
Capacity Optimization Working Group



World
Nuclear
Association

Title: Optimized Capacity: Global Trends and Issues
Produced by: World Nuclear Association
Published: November 2012
Series: WNA Report
Report No.: 2012/004

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Series information

The World Nuclear Association (WNA) is the body that supports the global nuclear industry. It achieves this through facilitating industry contact and cooperation, providing an extensive public information service and representing the industry at key international fora.

As part of its commitment to facilitating cooperation, the WNA's working groups are formed of experts drawn from the global nuclear industry who come together to address topics of shared interest. Working group members meet between three and four times a year and engage in an open exchange of information and opinions – continuing the well-established tradition of the sharing of knowledge and best practice within the industry.

Working group reports present the consensus views of these expert members on important specific issues. To this extent they provide a voice for the global nuclear industry; however the views of working groups do not necessarily reflect the views of any of the WNA's individual member companies.

Title information

This report reflects the research of the WNA's Capacity Optimization Working Group - a group constituted to identify means by which nuclear operators worldwide can both determine and attain their optimal capacity. In order to progress towards this goal, this report establishes a status baseline and undertakes high-level analysis to understand at what point the global industry currently stands and what the dominant issues in utilization of the installed capacity base are.

The first *Optimized Capacity: Global Trends and Issues* report was published in April 2010. That contained data series valid up to the end of 2008, however the popularity of the publication has led to this revised edition with data now extended to include the period up to the end of 2010. The main conclusions from the first edition remain largely unaltered. It is expected that from now on the report will be revised on a biennial basis.

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Executive Summary

This WNA report draws upon data collected in the International Atomic Energy Agency's (IAEA's) Power Reactor Information Service (PRIS) database to present a snapshot of the performance of the world's operating nuclear power reactors as well as a breakdown of the principal causes of capacity loss. This is the second edition of this report and covers the period to the end of 2010.

In the 20-year period from 1980 there was a significant rise in the median global actual energy utilization of reactors' maximum power capability – known as the capacity factor¹ – from 68%, culminating in 2002 in a historical maximum of 86%. Since around the turn of the century this growth has levelled off and has remained constant at around the 85% mark for the last ten years. However, best performers manage to consistently achieve around 95% or higher which suggests that renewed focus should be placed on optimizing capacity factors amongst the existing nuclear fleet.

In 2010 the global median capacity factor was 84.8%, but there was a very broad spread in this performance indicator between individual units. Generally, this variance is not explained by the reactor type used, or by age of the reactor. Indeed, the best performing units continue to represent a range of technologies, vendors and regions – suggesting that performance is not fundamentally limited by these factors.

Examining the performance of all plants globally, in recent years 94% of unavailable capacity is due to reasons under management control; the dominant cause being shut downs for planned maintenance combined with refuelling. Best performing operators have significantly shorter and better-controlled outages while still maintaining essential safety standards. Speaking more broadly, best performers maximize their availability and minimize their unplanned unavailability; they plan for success and are able to mitigate any contingencies.

It is seen that the major direct cause of unplanned loss is failure or problems with plant equipment, with the turbine and auxiliary system having the greatest effect, followed by electrical power supply systems and main generator systems. Of these, the electrical power supply systems have become substantially more significant as a source of unplanned loss in the two years since the publication of the first edition of this report.

Additionally we see that indicators of plant safety and capacity are linked: a well-managed plant is generally both productive and safe.

With potentially significant benefits available in economics, security, environmental performance and safety it is clear that further work on optimizing the current global nuclear fleet's capacity has merit. The Capacity Optimization Working Group continues to provide the global forum for helping the worldwide industry realize these benefits.

¹ Also sometimes known as the Load Factor.

1

Introduction

The electrical output of a nuclear power plant is dependent on a wide variety of factors. Within the boundaries set by these ‘real world’ issues it is desirable that a nuclear reactor should perform at its best achievable capacity, its optimized capacity. Additionally, the boundaries themselves can also be questioned, understood and influenced.

The benefits of moving towards the attainment of optimized capacity are numerous and include:

- ▶ **Safety** – enhancing nuclear and industrial health and safety through minimizing unplanned outages.
- ▶ **Economic** – maximizing the return on an asset-based business.
- ▶ **Energy Security** – contributing to the security and diversity of energy supply.
- ▶ **Environmental** – increasing power generation from non-greenhouse gas emitting power and making best use of available materials and resources.
- ▶ **Social** – improved public perception of nuclear as a clean, reliable and affordable energy source, capable of meeting a country’s long term base-load electricity needs.

In 2010 the world’s operating nuclear reactors generated 2,630 TWh of electricity, representing an average capacity factor² of 80.5% (median 84.8%). If this could be increased in relative terms by 10%, this would:

- ▶ Result in the production of an extra 263 TWh, an amount equivalent to connecting approximately 37.5 GW worth of new nuclear to the grid
- ▶ Avoid the emission of 260 million tonnes of carbon dioxide³.

The performance of the nuclear fleet should therefore be of interest to a wide audience including operators, financiers, policymakers and regulators, as well as the general public.

This report is intended as a broad overview of the global trends and identifies the topics that will be covered in greater depth in subsequent WNA working group initiatives.

² The capacity factor is a performance indicator which reflects the actual amount of electricity provided to the grid as a percentage of the maximum possible under reference conditions.

³ Estimated if coal had been used as a direct replacement.

2 Data Model

Figure 1 below shows the model that has been adopted to assess data values collected from nuclear power plants. The reference unit power is the maximum (electrical) power of the unit under reference ambient conditions. It is based on design values, adjusted for reference ambient conditions and is expected to remain constant unless design changes that affect the capacity are made to the unit. As shown in Figure 1, it can be split into two components, 'available capacity' and 'unavailable capacity'. The balance between these two components is determined by eight factors: outage execution, equipment reliability, regulatory environment, organizational factors, engineering, safety performance, finances and supply chain processes. These factors are expanded on in Section 5 of this report.

Further, 'available capacity' can be broken down into what is and what is not supplied to the grid. Similarly 'unavailable capacity' can be broken down into elements that are or are not under plant management control. Finding and achieving the optimal balance between 'generation supplied' and the other three components is the essence of WNA's work on capacity optimization.

Two additional important concepts can be defined using this model: 'availability' is the sum of the 'generation supplied' and 'available but not supplied'; 'capability' is the sum of the 'generation supplied' and 'available but not supplied' and the element of unavailable capacity which is 'not under plant management control'.

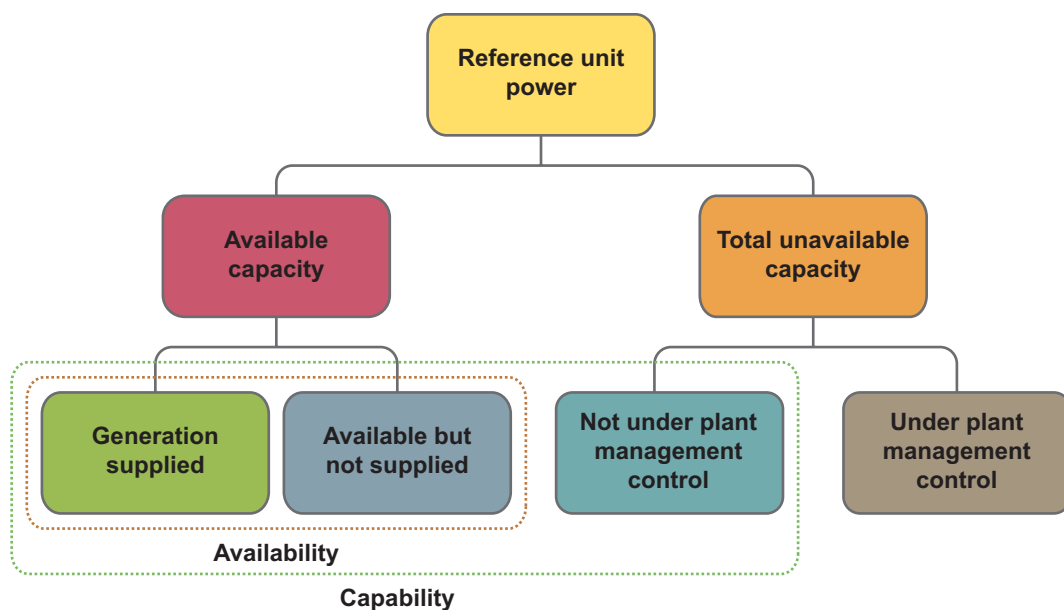


Figure 1: Data Model

In order to determine performance measures, the concept of reference energy generation (REG) is applied. It is determined by multiplying the reference unit power by the reference period⁴. By dividing the components at the lowest level of Figure 1 by REG, we derive a set of indicators that are used across the nuclear fleet. The relationship between values and indicators is shown in Figure 2.

⁴ The reference period is the time (in hours) over which the indicator is calculated.

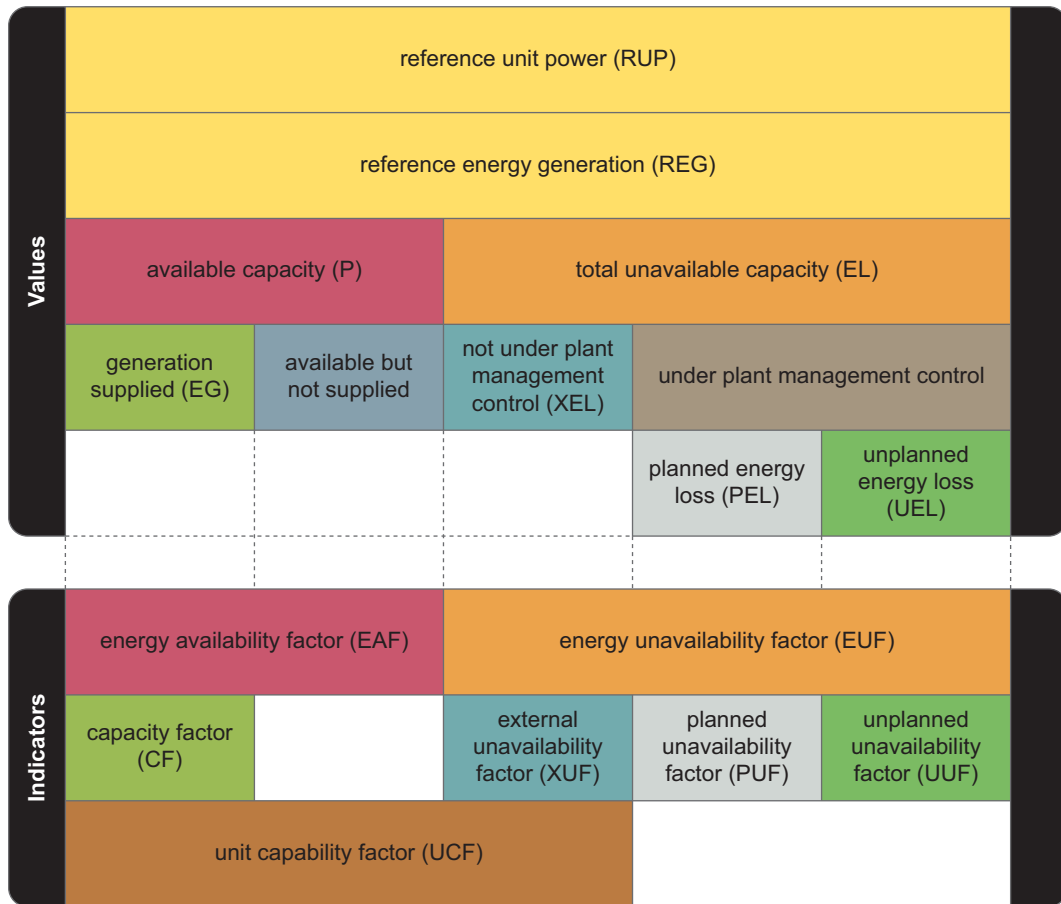


Figure 2: Performance Indicator Derivation

Performance indicators allow for meaningful statistical analysis of current and historic data held on the nuclear fleet. Of particular interest is the ‘capacity factor’ indicator that relates to the ‘generation supplied’ as discussed above.

More detailed definitions of these performance values and indicators can be found in Section 6 of this report.

Note: The data model, performance indicators and data used in this report are drawn from figures held in the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) which constitutes the most complete and authoritative technical data bank on nuclear power reactors in the world. The same terminology is also applied, with the exception of the capacity factor which the IAEA refers to as ‘load factor’.

3 Industry Trends

This section provides a summary of PRIS performance data as well as some high-level analysis in order to help better understand the issues facing the utilization of the current nuclear fleet.

Most of the analysis presented makes use of median capacity factors (CF) rather than averages, effectively removing weighting due to long-term shutdowns or chronically underperforming plant. The report is designed to highlight how most reactors are actually performing – rather than highlight those units which are shutdown for long periods due to regulatory reasons or major refurbishment.

To highlight the current limits of achievable performance, a distinction is drawn between the entire global fleet of nuclear reactors ('All' reactors) and the top performing 10% (best performers) as determined by their energy availability factor averaged over five years. Other performance indicators are then derived separately for these two groups. Availability is used instead of capacity factor so as not to exclude units which load follow or are subject to other grid limitations.

Several distinct time periods are referred to throughout. A snapshot of performance over one year is presented for 2010. However most plant operating cycles are longer than this, meaning that useful indicators must be derived over a longer period – five years was the period chosen (Jan 1 2006 - Dec 31 2010). A ten year period is also used to allow comparison over the longer term (Jan 1 2001 - Dec 31 2010). It should be noted that the individual units which comprise the best performers category will stay the same between these time periods. However they may change between the editions of the report.

3.1 GLOBAL OVERVIEW

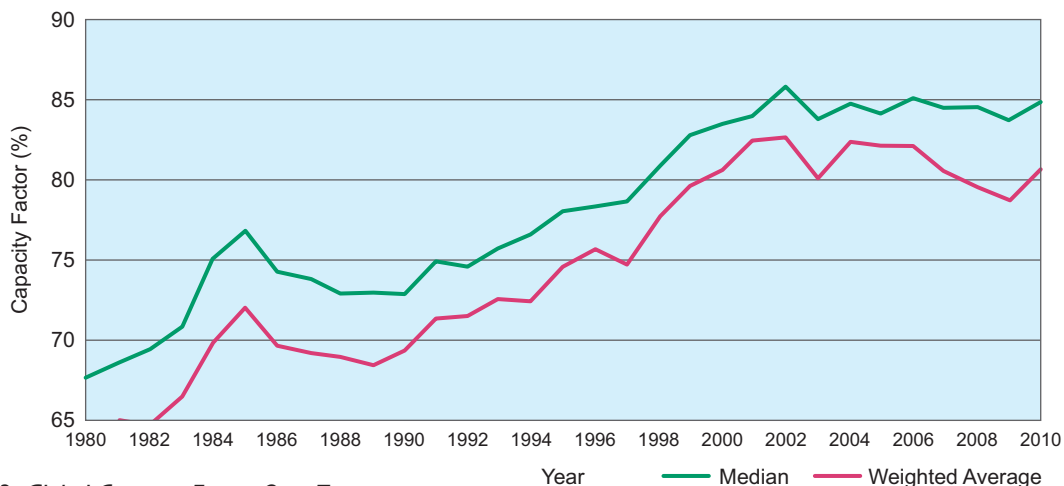


Figure 3: Global Capacity Factor Over Time

Figure 3 shows that in the 20-year period 1980-2000 there was almost a 20% rise in the median CF culminating in 2002 in a historical maximum of 86%. However, since around the turn of the century this growth has levelled off and has remained constant at around the 85% mark for the last 10 years.

Figure 4 indicates there is a long tail of reactors that for whatever reason perform well beneath the average. Improving these could result in substantial extra nuclear generation and drive up the average global CF, however it might have a negligible effect on the median value.

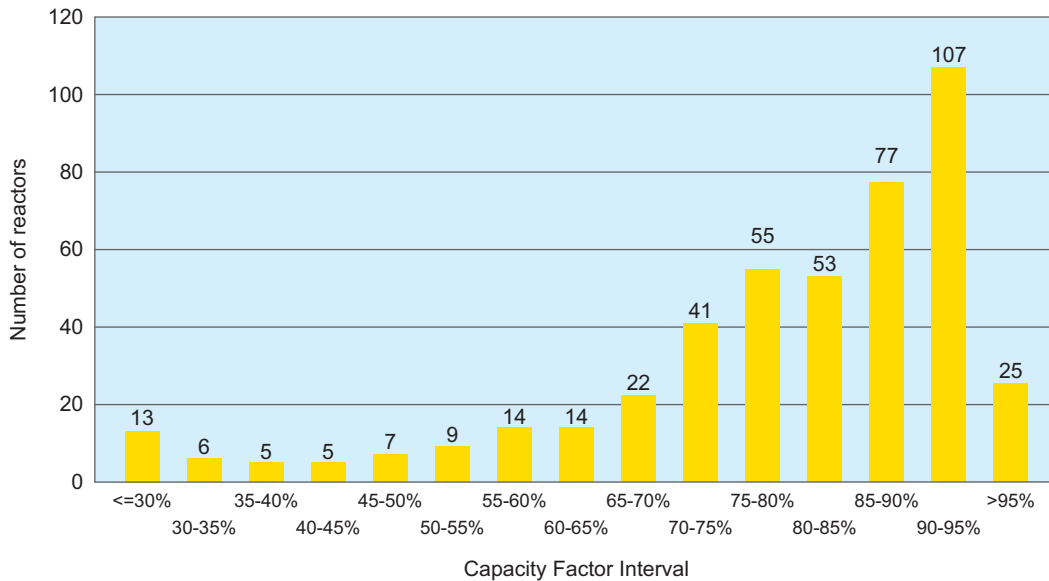


Figure 4: Histogram of Individual Plant Capacity Factors 2006-2010

The 20% rise in the period 1998-2000 was despite an 8 year 'recovery' in the CF following the Chernobyl accident in 1986. There have been some specific cases that have affected progress more recently:

- ▶ TEPCO case in 2003 – long-term shutdown of 17 TEPCO units (2003 and 2004)⁵.
- ▶ Earthquake at Kashiwazaki Kariwa in July 2007 – seven reactors shutdown for upgrades, as of February 2011 three units still not restarted.
- ▶ Long-term shutdown in 2007 of Brunbuettel and Kruemmel in Germany.
- ▶ Ageing of Nuclear Power Plants (NPPs) - extended reconstructions of several old reactor units (for example, in 2008 eight reactors were not operated for this reason).

These cases are indicated in Figure 5. The numbers are still low compared to the total number of operating reactors and therefore these specific cases are perturbations in a general trend of levelling off of capacity factors, not the cause of the trend.

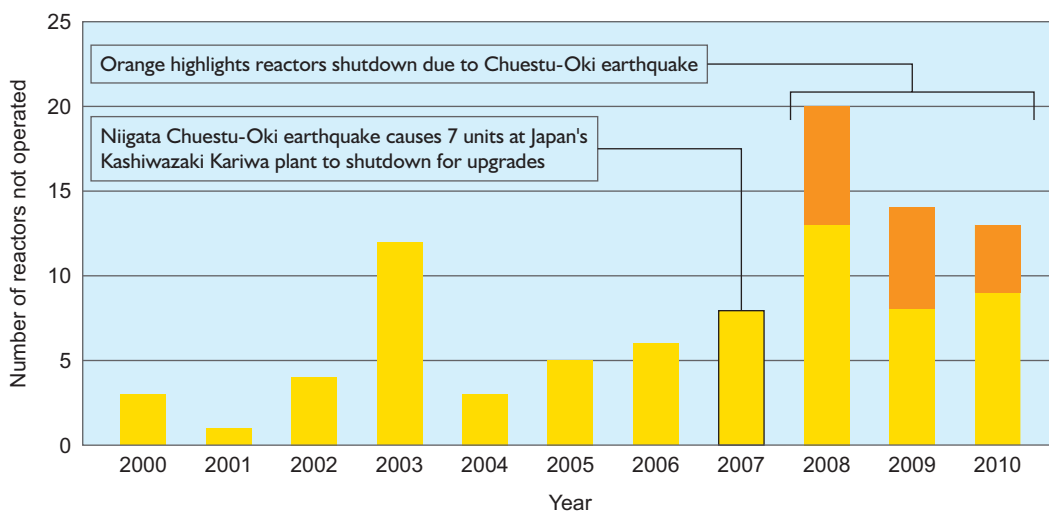


Figure 5: Number of Reactors Not Operated for the Entire Year

⁵ For most of these reactors the shutdown lasted less than one year.

It is also worth noting that the March 2011 accident at Fukushima Daiichi nuclear power plant - which effectively destroyed four reactors at the plant and caused the likely permanent closure of the two remaining units, as well as resulting in the immediate permanent shutdown of eight reactors in Germany and the temporary shutdown of the entire Japanese fleet – is outside the period of data collection for this report but will certainly affect the next edition.

While Figure 3 shows a global median average CF, the actual CF of individual plants varies and in some cases varies very widely from the worldwide median as demonstrated in Figures 4, 6 and 7. The fact there are differences, the causes of which are not necessarily understood, is the basis for the WNA’s Capacity Optimization Working Group’s work. The first step along the path to improvement is understanding these differences.

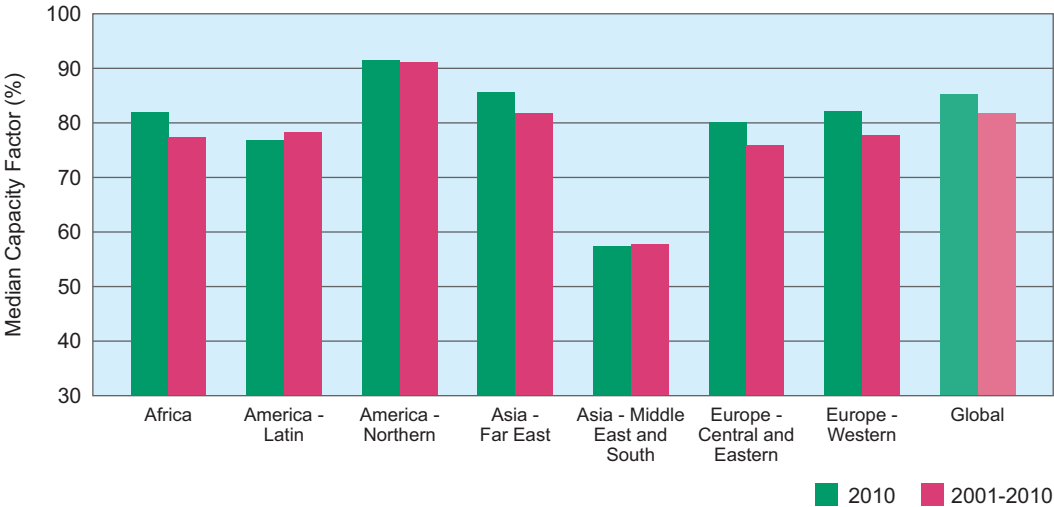


Figure 6: Long and Short Term Median Capacity Factors by Region

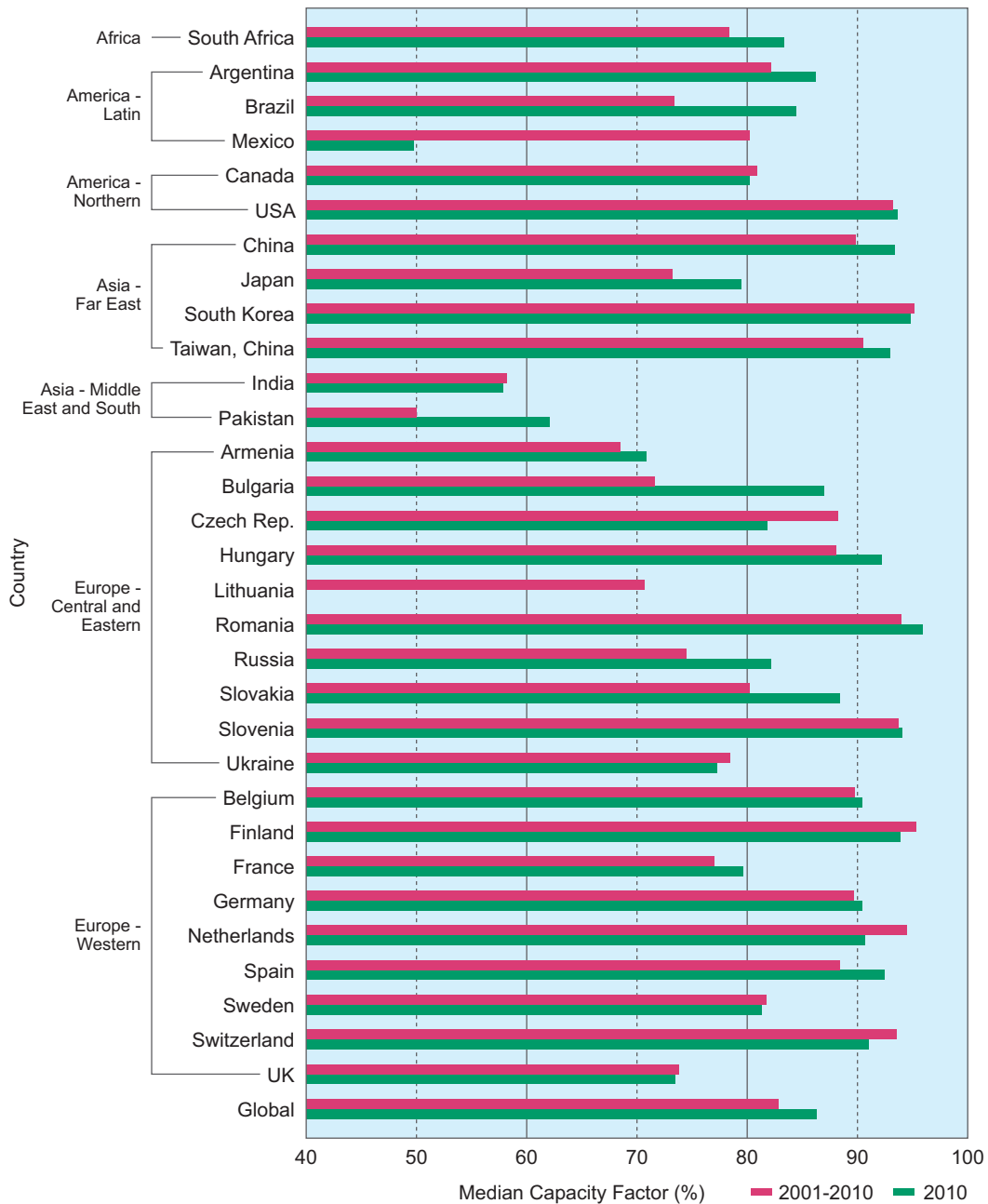


Figure 7: Long and Short Term Capacity Factors by Country⁶

Figures 6 and 7 have been included to demonstrate the variation from the global median based upon region. There is a wide spread of CFs between regions and between countries within the same region. Local conditions can be seen to come into play more directly (for example fuel supply issues, seasonal demand variations, load following). While regions and countries may have restraints imposed on them by their local conditions, all can look to continuously improve performance within these boundaries.

Countries and regions will always be an important common denominator due to national and regional regulatory control. However, companies and workforces are becoming increasingly internationalized over time, while efforts are ongoing towards harmonising codes and standards. If this trend towards globalization continues in the nuclear industry it will reduce the importance of reactor nationality.

⁶ Lithuania's only operating reactor, Ignalina-2, shutdown at the end of 2009.

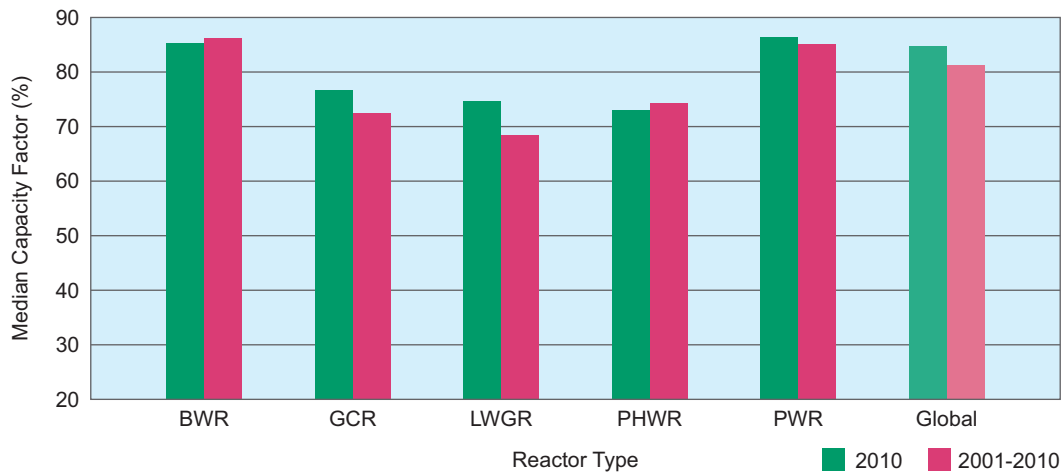


Figure 8: Long and Short Term Capacity Factors by Reactor Type

BWR – Boiling Water Reactor (including ABWR)

GCR – Gas Cooled Reactor (including AGR)

LWGR – Light Water Graphite Reactor (also known as RMBK)

PHWR – Pressurized Heavy Water Reactor (including CANDU)

PWR – Pressurized Water Reactor (including VVER)

The PWR and BWR designs together account for over 80% of operating units. Figure 8 shows that there is effectively no difference between their global CFs over time. The ageing mechanisms, chemistry performance, and standard equipment are very different between these technologies, as are the operations, especially with respect to refuelling requirements. Yet, despite these differences, both technology types achieve similar performance, suggesting that technology is not a fundamental limiting factor to sustainable and efficient operation. The next most prevalent reactor type is the PHWR, followed by the GCR and LWGR. Only one Fast Breeder Reactor (FBR) is currently operating and therefore has been excluded from the statistical analysis in this report⁷.

The high availability of PWR, PHWR and BWR reactors is despite decreased performance of some BWR and PHWR reactors in the last few years. The availability of BWR units has been significantly affected by the TEPCO case in 2003 and the earthquake in Japan in 2007 (all TEPCO units are BWRs). Had these units been operating at, or near, maximum practical capacity factor, the recent events would have resulted in a downturn in the (median) capacity factor of this technology type. This suggests that there is a strong reserve margin of capacity to be realized through operational best practices.

Performance of GCRs has varied significantly, mainly due to type-specific ageing plant issues, as opposed to operational issues. The 2010 capacity factor of 77% is a pronounced increase on the 2008 value of 62%; and is mainly due to the end of boiler inspection and modification work which took place during 2007 and 2008 in several AGR units. As for the other type of graphite moderated reactor, LWGRs have increased their availability significantly over the last few years.

⁷ There is significant variation between FBRs which are broadly describable as prototypes. Despite this, the Russian designed BN-600 Beloyarsky-3 has recorded a lifetime capacity factor to date of 74%, boding well for future deployment of this design. The Japanese designed MONJU reactor restarted in 2010 after a 14 year shutdown, though has not yet re-connected to the grid.

The above illustrates a requirement to better understand the root cause for poor performance, specifically whether it is an operational issue or an ageing issue, so as to focus the industry effort on the most promising areas for performance improvement.

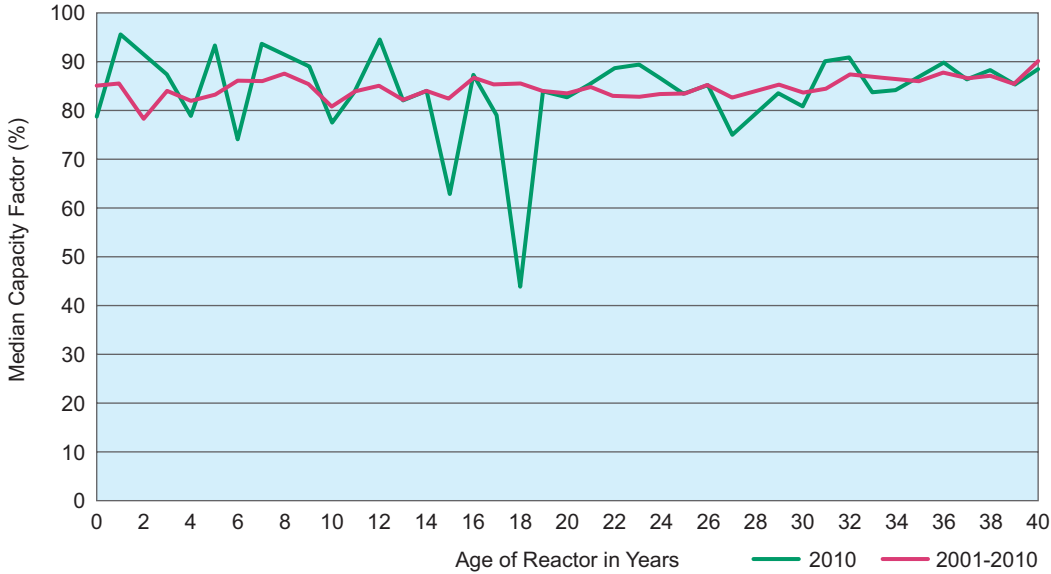


Figure 9: Long and Short Term Capacity Factors by Reactor Age

In general, no significant global age-related trend in capacity factor can be detected from Figure 9. This is good news for older plants, which can maintain historic output levels, and also for newer plants, which do not appear to require any ‘run-in’ time, suggesting that industrial good practice in operations is being passed on. It is uncertain whether genuinely new designs, such as the EPR and API000, will benefit from this. There may well be a learning curve for the first couple of units.

Figure 5 shows a general increase in the number of reactors off line for an entire year - with a peak in 2008. It is believed that this is partly caused by increasing numbers of ageing reactors coming off line for major items to be refurbished – even accounting for the effects of the Niigata Chuestu-Oki earthquake. Therefore, there are some ageing effects on the fleet which are being managed, however Figure 9 suggests that ageing reactors that are on-line are operating as well as new reactors.

What cannot be seen here is the cost of keeping older plants performing at historic levels, and whether this cost is comparable with the cost of operating younger plants⁸. It is also important to remember that capacity factor here is different from output – older plants tend to have significantly lower reference unit power.

While Figure 9 gives an overview, it is suspected that there will be trends hidden within it. A further, more detailed analysis of ageing requires investigation by reactor type and reactor model. It also requires filtering to manage those cases when the capacity factor is affected by a non-ageing reason, such as an earthquake.

⁸ In many cases it will actually be much lower as the initial capital and financing costs are paid off.

3.2 UNAVAILABLE CAPACITY

As shown in Figures 1 and 2, the power of a unit can be split into two parts; the Available Capacity (AC) and the Total Unavailable Capacity (UC). UC results in energy loss (EL) that can be further broken down into three components:

PEL – planned energy loss

UEL – unplanned energy loss. (UEL can be further broken down to forced energy loss during operation and unplanned extension of outages when the reactor is shut down.)

XEL – external loss. Loss that is not under plant management control

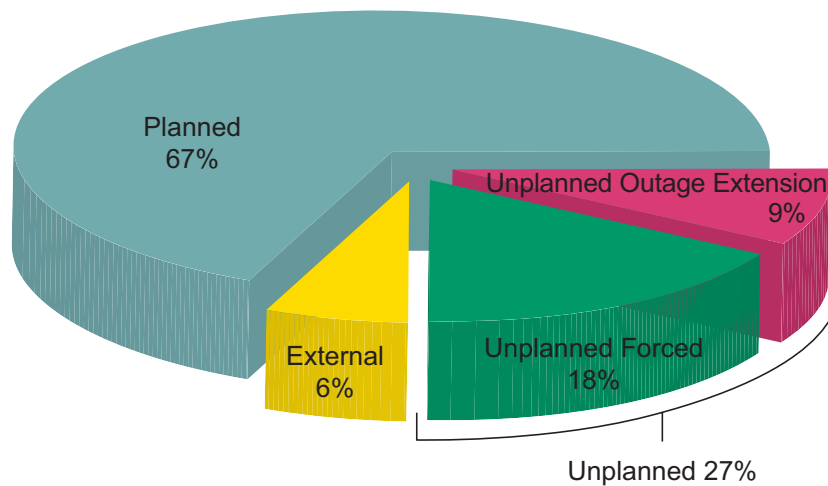


Figure 10: Energy Loss Distribution (2006-2010)

Figure 10 shows that globally, 94% of unavailable capacity is within plant management control. Planned losses are the most significant factor, followed by unplanned losses. External reasons, which are not under plant management control (eg. Fuel coast down operation, environmental limitation), are the smallest cause. In Figure 10 unplanned losses which are under plant management control have been split into two components, demonstrating the importance of unplanned extensions of planned outages. Clearly planned losses are most important, but unplanned causes should also be addressed – especially since they tend to entail extra economic consequences to operators such as replacement power and corrective maintenance costs.

Median	Capacity Factor	Planned Unavailability Factor	Unplanned Unavailability Factor	External Unavailability Factor	Forced Loss Rate
Totals:	83.20	9.88	2.21	0.25	1.77
BWR	85.51	8.77	2.11	0.08	1.53
GCR	65.65	10.79	20.46	0.01	15.74
LWGR	71.05	18.91	1.52	0.94	1.21
PHWR	72.65	8.20	4.06	0.59	3.95
PWR	85.31	9.86	1.55	0.25	1.32

Figure 11: Performance Indicator by Reactor Type (2006-2010)

Best Quartile	Capacity Factor	Planned Unavailability Factor	Unplanned Unavailability Factor	External Unavailability Factor	Forced Loss Rate
Totals:	90.79	7.08	0.73	0.00	0.63
BWR	91.46	6.13	0.75	0.00	0.47
GCR	81.10	7.80	8.22	0.00	8.57
LWGR	80.25	15.34	0.60	0.37	0.45
PHWR	88.46	5.78	1.91	0.09	1.87
PWR	91.34	7.27	0.62	0.00	0.50

Figure 12: Best Quartile Performance Indicator by Reactor Type (2006-2010)

Demonstrated again in Figures 11 and 12 is that planned losses are most significant for all reactor types, except in the case of GCRs, where unplanned losses are most significant.

3.2.1 PLANNED ENERGY LOSS

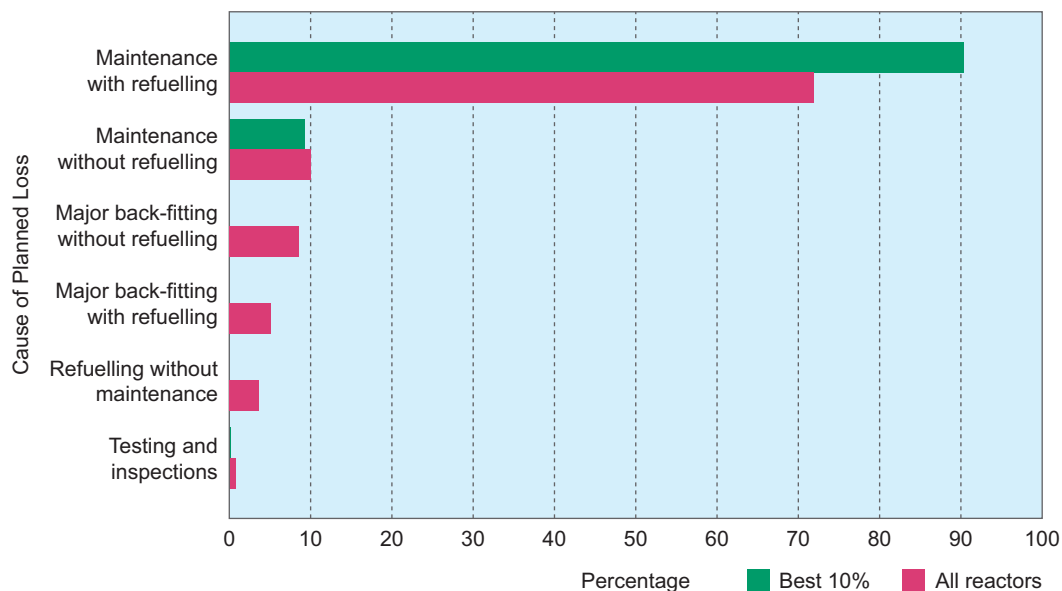


Figure 13: Planned Energy Loss Causes (2006-2010)

Figure 13 looks at planned loss in more detail. It can be seen clearly that a combined maintenance and refuelling outage is the dominant cause for all units, accounting for approximately 72% of this category⁹. This is much the same as it was for the first edition of this report. Looking at the best performing 10% of reactors we can see this situation is exaggerated further. In best performers a combined maintenance and refuelling outage accounts for close to 91% of incidences of planned loss (compared to 88% two years ago).

Over the past two years there has been an approximate doubling of the planned energy loss caused by units undergoing major back-fitting – both with and without refuelling. As reactor lifetimes of greater than 40 years increasingly become the global norm we can expect to see more of this kind of shutdown.

⁹ Figures 13, 15 and 16 refer to the relative number of initiating causes, not the amount of time lost to these events.

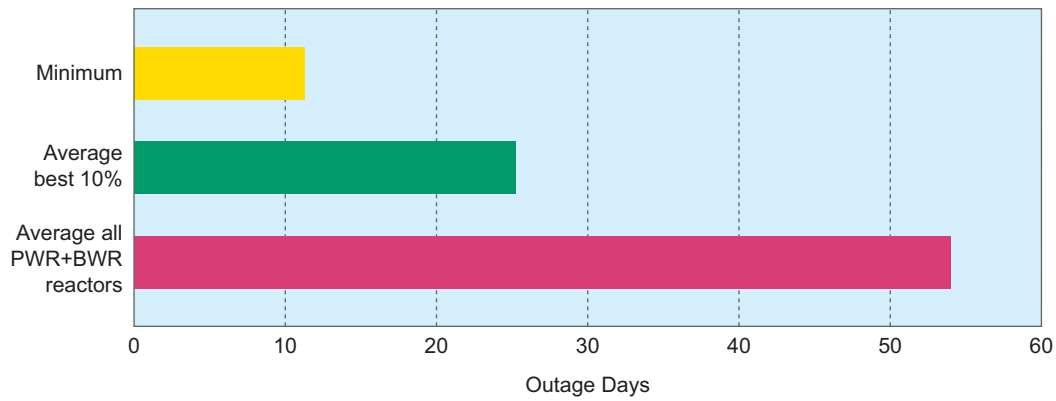


Figure 14: Refuelling Outage Durations for BWR and PWRs (2010)

We can see in Figure 14 that best 10% of have less than half the average outage duration. Clearly a short refuelling duration is a key feature of best performance.

3.2.2 UNPLANNED ENERGY LOSS

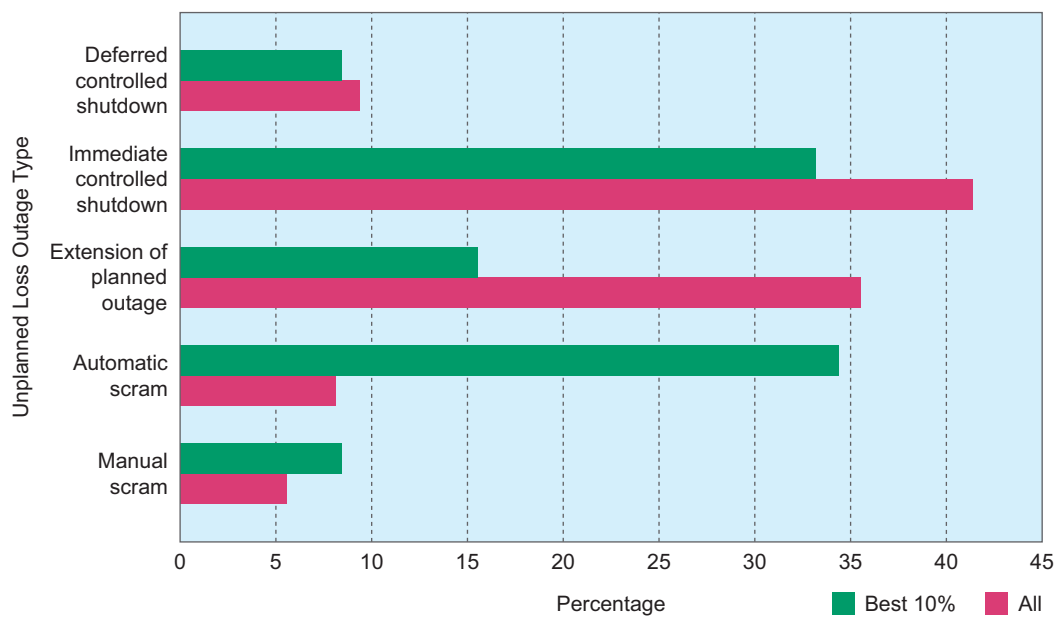


Figure 15: Unplanned Energy Loss by Outage Type (2006-2010)

Figure 15 looks at the various causes of unplanned losses for 'All' reactors and best performers. The biggest variations are to be found in extension of planned outages and automatic scrams. Scrams become a comparatively more important source of energy loss as other sources become better controlled. However this increase is relative to other sources of loss only and does not mean that more production is lost to these events.

Note: The average energy loss per year due to automatic scrams is 22.5 GWh per reactor for best performers and 41.5 GWh for 'All' reactors, while the average outage frequency per reactor year due to automatic scrams is 0.25 and 0.37 respectively. For immediate controlled shutdowns, another safety indicator, the figures are (energy loss) 17.7 GWh for best performers and 113.2 GWh for 'All' reactors, and (outage frequencies per year) 0.25 and 0.75 respectively.

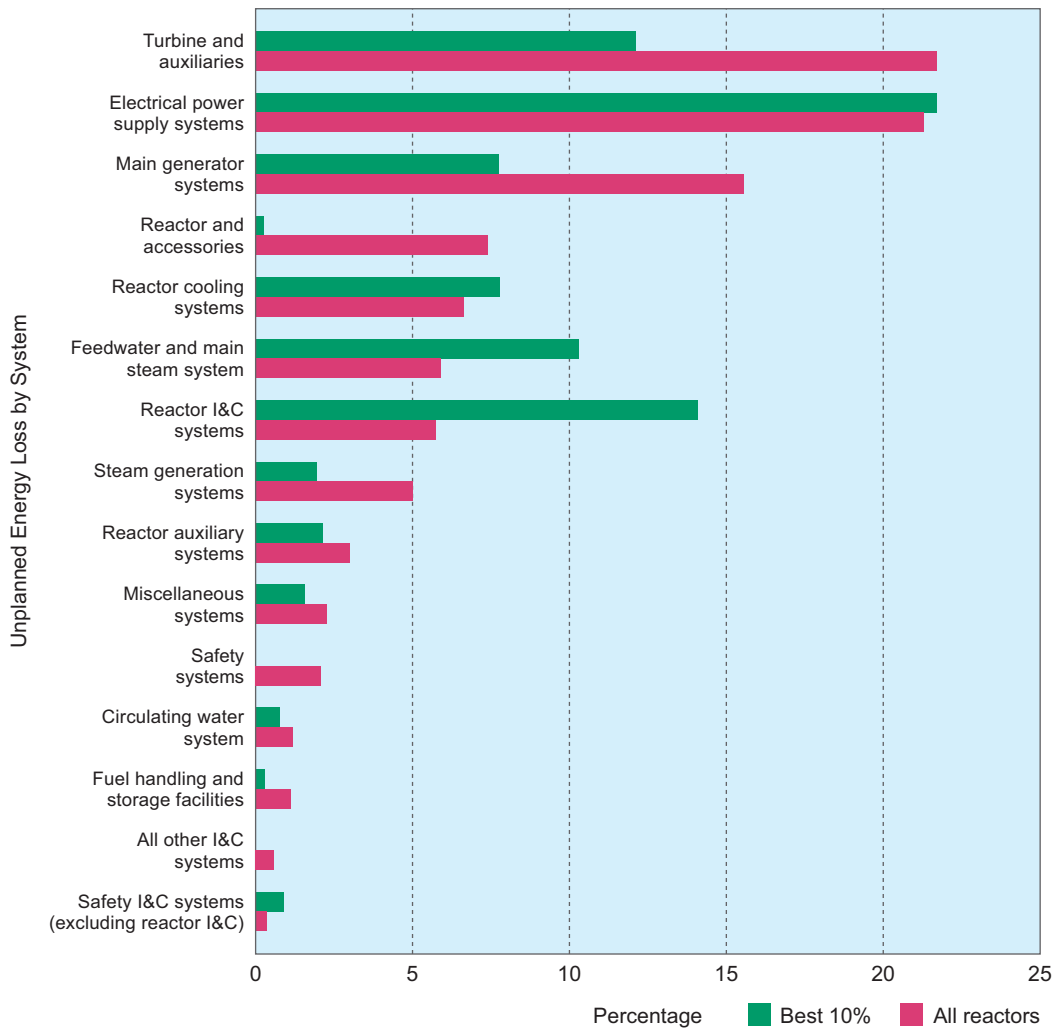


Figure 16: Unplanned Energy Loss by System (2006-2010)

Figure 16 shows the causes of unplanned energy loss by system. The distribution of systems directly involved in unplanned energy losses for best performers is markedly different from that of 'All' reactors. For both groups, turbine and auxiliary systems and electrical power supply system are major contributor to loss, while the main generator systems are a significant factor for 'All' reactors and I&C systems are important for best performers.

For turbine and auxiliary systems this resulted in an average energy loss per reactor year of 7.1 GWh (average outage frequency: 0.16) for best performers and 43.7 GWh (average outage frequency: 0.32) for 'All' reactors; whereas electrical power and supply systems caused an average energy loss per year of 13.6 GWh for best performers (outage frequency: 0.10) and 38.7 GWh for 'All' reactors (outage frequency: 0.15).

These rankings are evolving. In the first edition of this report which contained data for the period 2004 - 2008, turbine and auxiliaries was the primary factor for both categories. Electrical power supply systems have recently become more of an issue for both categories, leaping from fifth to second place. Not enough detailed data exists to perform an adequate analysis of what is driving the problems within each of these systems. Good quality equipment/component failure data to identify common causes and therefore prevent them would be of benefit to the industry. The sharing of root cause analysis information on equipment and system failures could result in global gains.

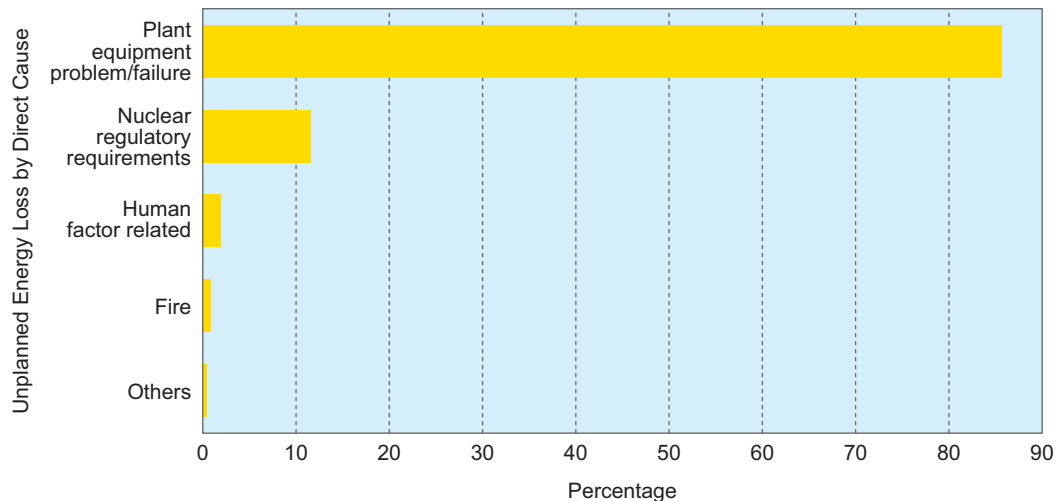


Figure 17: Unplanned Energy Loss by Direct Cause (2006-2010)

Figure 17 shows that the direct cause of unplanned energy loss is overwhelmingly attributable to equipment problems and failure. As with the systems analysis in Figure 16, not enough detailed data is available to analyse this further. Additionally, while direct cause is the immediate initiator for the unplanned loss and therefore understanding this is important, it is of limited value compared to understanding root cause, which is the initiating event or omission in the chain of events leading to the unplanned loss. It is suspected that root cause analysis for unplanned energy loss events would reveal a very significantly higher proportion of human factor-related causes, as well as attributing some blame to maintenance strategy, design or aging. However, this cannot be substantiated, as the information required for root cause analysis for unplanned energy loss is currently unavailable.

3.3 AVAILABLE CAPACITY

The other element of reference unit power is available capacity (AC), the indicator of which is the Energy Availability Factor (EAF). EAF is made up of both generation supplied to the grid and generation available but not supplied. The indicator that relates solely to generation supplied is the Capacity Factor (CF).

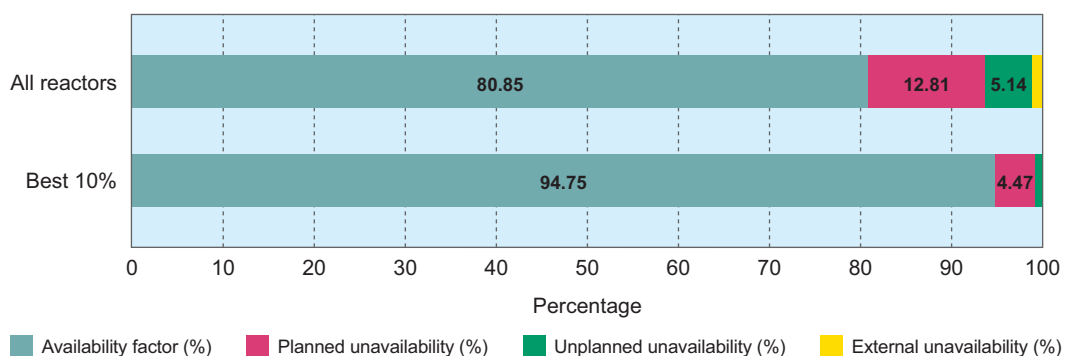


Figure 18: Availability of Reactor Units (2006-2010)

Figure 18 shows that best performers maximize their availability and minimize the amount of planned and unplanned unavailability compared to other units. For best performers then, planning for success and being able to stick to that plan is important.

Together, Figures 14 and 18 show that shorter outages do not result in increased losses in other categories, suggesting that the quality of the shorter outages is as good, if not better, than that of longer outages.

Outage scope does not have to be cut, and risk does not have to be transferred onto the operating cycle. It follows that there are clear efficiency gains to be made by lower performing units in this area.

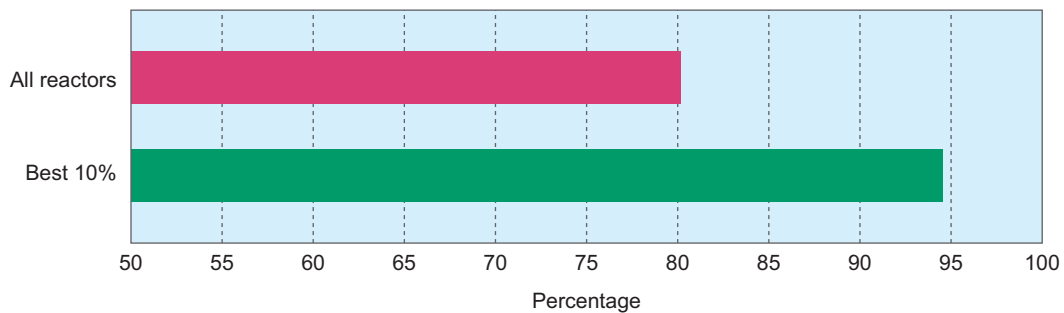


Figure 19: Recent Capacity Factors (2006-2010)

In Figure 19 the difference in achieved capacity factors between the best performing 10% of units and the global average is clear to see.

The best capacity factor performers in the years 2006-2010 represent a range of technologies¹⁰, vendors, regions¹¹ and countries; suggesting that performance is independent of these choices. Best performers in these years achieved a median capacity factor of 94.7%.

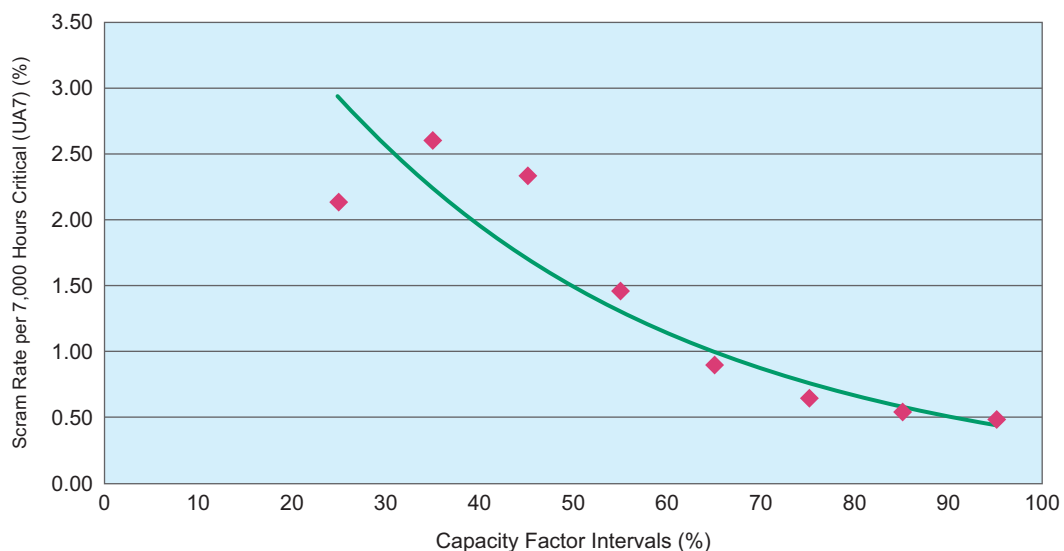


Figure 20: Average Number of Automatic Scrams for Capacity Factor Intervals (2006-2010)
Trend line inserted through data points.

The indicator Automatic Scram Rate per 7,000 Hours Critical (UA7) relates to plant safety as it provides a measure of undesirable and unplanned thermohydraulic and reactivity transients requiring reactor scrams. It also therefore provides an indication of how well a plant is being operated and maintained and indeed, it is seen in Figure 20 that there is a correlation between plant safety and performance. A higher CF is linked to lower numbers of automatic scrams. This is not to say that units which undergo scrams are unsafe. Scrams are caused by a wide range of issues including equipment problems and human performance issues as well as nuclear safety. They are one of a reactor's primary lines of defence against a possible accident condition. Nevertheless, best performers manage across these operational issues to minimise scrams and achieve both productivity and safety.

¹³ PWR, BWR and PHWR all appear in the list of best performers.

¹⁴ North America, Far East Asia and Europe all appear in the list of best performers.

4 Conclusions

1. The industry's steady progress in raising the capacity factor has halted in the last few years.
2. Age does not have a significant effect on the capacity factor.
3. Technology choice between the predominant reactor designs does not have a significant effect on the capacity factor.
4. Best performers have lower planned unavailable capacity than other reactors.
5. The vast majority of loss is within plant management control.
6. Planned losses are the biggest contributor to energy loss (except in the case of GCRs).
7. Combined maintenance and refuelling outages are the single biggest cause of planned energy loss – this is more pronounced for the best performers who comparatively reduce other causes of loss.
8. One of the biggest cause of unplanned energy loss is an extension to a planned outage – suggesting not only short outages but also well-planned and executed, predictable outages are beneficial.
9. Plant equipment problems and failure is the largest direct cause of unplanned energy loss, with the turbine and auxiliary system and electrical power supply systems responsible for the highest proportion of this.
10. Plants with higher capacity factors have lower numbers of automatic scrams.

These conclusions have been drawn using indicators of performance (capacity factors) for the global fleet and the best performing 10% of reactors. To draw more locally applicable conclusions would require the sorting and analysis of the data by factors such as region and reactor type.

Greater detail and understanding of performance would certainly be achieved by conducting case studies and root cause analysis. Root cause analysis applied to unplanned energy losses would result in information which could be applied to achieve gains globally. However, adequate data collection and sharing of this potentially sensitive information must first be undertaken by the industry in order to enable this analysis to be performed. It is the area of equipment reliability which most invites scrutiny. A more detailed investigation here could yield valuable insights into the effects of different codes and standards, human factors, plant aging, plant design, and maintenance strategies to name a few.

Within the category of planned losses, refuelling and maintenance outages stand out as being the area where by far the most positive gains can be readily achieved. Identifying what operators do differently and the subsequent sharing of best-practice and technology among the industry could go a long way to achieving the stated aims of the Capacity Optimisation Working Group. It is with this in mind that the Group has started to look at ways to encourage operators worldwide to share information on their template refueling outages in order to help identify the areas where best practices could lead to time savings.

With definite scope for improvement and potential benefits in safety, economics, security and environmental performance available, it is clear that further work in optimizing the current global nuclear fleet's capacity has merit.

5 Factors Affecting Capacity

The Capacity Optimization Working Group has identified the following factors as affecting capacity:

1. Outages

- ▶ Duration
- ▶ Frequency
- ▶ Scope
- ▶ Management
- ▶ Cost
- ▶ Planning

2. Equipment Reliability

- ▶ User interface
- ▶ Lifecycle management, asset management
- ▶ Predictive maintenance
- ▶ System redundancy
- ▶ Component failure
- ▶ System diagnostics
- ▶ Culture of operations
- ▶ Digital controls

3. Regulatory and Market Environment

- ▶ Licences/licensing
- ▶ Working regulations
- ▶ Market conditions
- ▶ Baseload vs. load following
- ▶ Fuel loading cycles (12, 18, 24 months)
- ▶ Greenhouse gas emission abatement schemes
- ▶ Public relations
- ▶ Fuel availability
- ▶ Surveillance extensions (component level)
- ▶ Mandated outage operations requirements
- ▶ Life extension

4. Organizational Factors and Human Performance

- ▶ Human resource availability
- ▶ Training and education requirements
- ▶ Safety culture
- ▶ Knowledge management
- ▶ Governance (centralized/decentralized)
- ▶ Financial decision making – financial steering model
- ▶ Worker satisfaction – strikes

5. Engineering

- ▶ Design changes
 - Power uprates
 - Plant modernization
 - Design change processes (life cycle management)
- ▶ Fuel
 - Design
 - Reliability
 - Front and back end (limiting factor)
- ▶ Environment
 - Water
 - Heat sink
 - Hurricane
 - Earthquake
 - Tsunami/Flooding
- ▶ Grid stability
- ▶ Ageing – longer term management
- ▶ Thermal performance

6. Safety Performance

- ▶ Scrams
- ▶ Controlled shutdowns

7. Finances

- ▶ Cost benefit
- ▶ Investment analysis

8. Supply Chain Processes

- ▶ Contract management
- ▶ Partnerships and alliances
- ▶ Procurement

6 Definitions

For more detailed definitions and descriptions of accepted measurement techniques for the following values and performance indicators please refer to either:

- ▶ IAEA PRIS or
- ▶ World Association of Nuclear Operators Performance Indicator Programme Reference Manual

6.1 VALUES

Reference Unit Power (RUP)

The maximum power capability of the unit under reference ambient conditions. Reference ambient conditions are environmental conditions representative of the annual mean (or typical) ambient conditions for the unit. The reference unit power remains constant unless permanent modification or permanent change in authorization that affects the capacity is made to the unit. [MW(e)]

Reference Energy Generation (REG)

The energy that could be produced if the unit were operated continuously at full power under reference ambient conditions. The reference energy generation is determined by multiplying the reference unit power by the period hours. [MW(e).h]

Available Capacity (P)

The maximum net capacity at which the unit or station is able or is authorized to be operated at a continuous rating under the prevailing condition assuming unlimited transmission facilities. [MW(e)]

Energy Loss (Total Unavailable Capacity) (EL)

The energy which could have been produced during the reference period by the unavailable capacity. It is comprised of PEL, UEL and XEL. [MW(e).h]

Energy Generated (Generation Supplied) (EG)

The net electrical energy supplied during the reference period as measured at the unit outlet terminals, i.e. after deducting the electrical energy taken by unit auxiliaries and the losses in transformers that are considered integral parts of the unit. [MW(e).h]

External Energy Losses (XEL)

The energy that was not supplied due to constraints beyond plant management control that reduced plant availability. [MW(e).h]

Planned Energy Loss (PEL)

The energy that was not supplied during the period because of planned shutdowns or load reductions due to causes under plant management control. Energy losses are considered to be planned if they are scheduled at least 4 weeks in advance. [MW(e).h]

Unplanned Energy Loss (UEL)

The energy that was not supplied during the period because of unplanned shutdowns, outage extensions or load reductions due to causes under plant management control. Energy losses are considered to be unplanned if they are not scheduled at least 4 weeks in advance. [MW(e).h]

6.2 INDICATORS

Capacity Factor (CF)

The ratio of the energy which the unit produced over the period, to the reference energy generation over the same time period

$$CF (\%) = (EG/REG) \times 100$$

This indicator reflects the actual energy utilization of the unit for electricity and heat production.

(Note: this is sometimes known as Load Factor (LF))

Energy Availability Factor (EAF)

The ratio of the energy that the available capacity could have produced during this period, to the reference energy generation over the same time period.

$$EAF (\%) = [(REG-PEL-UEL-XEL)/REG] \times 100$$

This indicator reflects the unit's ability to provide energy.

Energy Unavailability Factor (EUF)

The ratio of the energy losses during the period due to unavailable capacity to the reference energy generation over the same time period.

$$EUF (\%) = (EL/REG) \times 100 = 100 - EAF = PUF + UUF + XUF$$

This indicator reflects all the unit's energy losses.

Unit Capability Factor (UCF)

The ratio of the energy that the unit was capable of generating over a given time period considering only limitations under plant management control, to the reference energy generation over the same time period.

$$UCF (\%) = [(REG-PEL-UEL)/REG] \times 100$$

This indicator reflects the unit's energy production reliability.

Planned Capability Loss Factor (PCLF)/Planned Unavailability Factor (PUF)

The ratio of the planned energy losses during a given period of time, to the reference energy generation over the same time period.

$$PCLF/PUF (\%) = (PEL/REG) \times 100$$

This indicator reflects planned activities that cause energy loss such as refuelling and maintenance.

Unplanned Capability Loss Factor (UCLF) /Unplanned Unavailability Factor (UUF)

The ratio of the unplanned energy losses during a given period of time, to the reference energy generation over the same time period.

$$UCLF/UUF (\%) = (UEL/REG) \times 100$$

This indicator reflects outage time and power reductions that result from unplanned equipment failures or other conditions.

External Unavailability Factor (XUF)

The ratio of the external energy losses during a given period of time, to the reference energy generation over the same time period.

$$XUF (\%) = (XEL/REG) \times 100 = UCF - EAF$$

This indicator reflects energy loss caused by events beyond plant management control.

Forced Loss Rate (FLR)

The ratio of all unplanned forced energy losses during a given period of time to the reference energy generation reduced by energy generation losses corresponding to planned outages and unplanned outage extensions of planned outages during the same period.

$$\text{FLR (\%)} = \text{FEL} / [\text{REG} - (\text{PEL} + \text{OEL})] \times 100$$

where FEL is unplanned forced energy losses and OEL is unplanned outage extension losses.

This indicator reflects the plant's ability to maintain systems for safe electrical generation when it is expected to be at the grid dispatcher's disposal.

Automatic Scram Rate per 7,000 Hours Critical (UA7)

The number of unplanned automatic scrams (reactor protection system logic actuations) that occur per 7000 hours of critical operation. This indicator reflects plant safety (the number of undesirable and unplanned thermal-hydraulic and reactivity transients requiring reactor scrams).

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The Capacity Optimization Working Group wishes to express its thanks to the International Atomic Energy Agency for access to and generous assistance with using the Power Reactor Information System.

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