Excellence in Power

Indo-German Energy Forum

FLEXIBILITY TOOLBOX – MEASURES FOR FLEXIBLE OPERATION OF COAL-FIRED POWER PLANTS

Study by:

VGB POWERTECH

Supported by:

सत्यमेव जयते

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Excellence Enhancement Centre for Indian Power Sector (EEC)
West Block - 2, First Floor
Wing No. 5, Sector 1, R.K. Puram
New Delhi 110066, India
Email: info@eecpowerindia.com
Website: www.eecpowerindia.com
Tel.: +91 11 26164297 - 95

Indo-German Energy Forum Support Office (IGEF-SO)
c/o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
1st Floor, B-5/2, Safdarjung Enclave
New Delhi 110 029, India
Email: info@energyforum.in
Website: www.energyforum.in
Tel.: +91 11 4949 5353

Project lead:
O.P. Maken, EEC
Tobias Winter, IGEF-SO
on behalf of Task Force Flexibility

Study by:
VGB Power Tech e.V.
Deilbachtal 173
D-45257 Essen, Germany
Website: www.vgb.org

Contact:
Dr. Oliver Then, VGB PowerTech e.V.
Dr. Claudia Weise, VGB PowerTech e.V.
Mr. Heinrich Grimmel, VGB PowerTech e.V.
Jörg Kaiser, VGB PowerTech e.V.
Dr. Christoph Guder, STEAG
Dr. Daniel Lehmann, STEAG
Manfred Schesack, STEAG

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Executive Summary

The increased share of feed-in from fluctuating renewable energies – mainly wind and solar – results in complex challenges for the energy system. In addition to other options such as grid and demand-side management, flexible conventional power generation plays a key role for ensuring adequate system stability. Therefore, existing coal-fired power plants need to adapt to a completely new operating regime.

Low minimum load is the most important flexibility dimension:

Flexible power plant operation comprises three dimensions: low minimum load operation, short and efficient start-ups and shut-down, and high ramprates. Most measures for flexibility enhancement aim at low minimum load operation. This is very important for the provision of residual load and in times of low demand, it is more economic than shutting down the whole plant.

The transformation from base-load to flexible operation is a change process that requires strong management and leadership, skilled employees and appropriate technology. There is no generic concept or single implementation plan for power plants, as each plant has its own specifics, technology requirements and site conditions. However, there are some actions and steps that need to be taken in order to tap the flexibility potential of a single plant.

10 Steps to Flexibility

1. **Raise the awareness for flexibility:**
   Provide background information about the need for flexibility, explain the necessity and impact on the O&M of the plant, and initiate training programs.

2. **Check the status of the plant and identify bottlenecks and limitations with respect to flexible operation:**
   - Consult with OEMs to assess the influences of low load operation and temperature and pressure gradients on main components and equipment.
   - Ensure smooth operation of all control loops at base load.
   - Plan and execute test runs to evaluate the plant flexibility potential
   - Create transparency about the plant performance with respect to minimal load, start-up and cycling behavior in the current setup.
   - Identify constraints and process limitations as well as improvement potential.

4. **Optimize the I&C system:**
   This is the most cost-effective way to enhance the flexibility of the plant. A certain level of automation is a prerequisite for tapping this potential.
   - Smooth control of major power plant processes is a flexibility enabler; e.g. precise steam temperature control.
   - Optimizing the underlying control loops, i.e. coal supply, drum level and air control, is a basic requirement and plant operators need to consider interlocks coming from logics.

5. **Implement mitigation measures** to manage the consequences of flexible / cycling operation. This includes a reassessment of all O&M procedures, with a special focus on water and steam quality, preservation and layup procedures as well as on maintenance strategies. The use of appropriate condition monitoring systems is essential.

6. **Optimize combustion:**
   Stable combustion is the key aspect to ensure minimum load operation. The following aspects are very important:
   - Reliable flame detection for each individual burner
   - Transparency about the coal quality and composition
   - Optimized air flow management
   - Operation with a reduced number of mills
   - Adaptation of the boiler protection system to low load operation.

7. **Optimize start-up procedures:**
   In order to ensure a fast and efficient start-up, plant operators should check start-up related temperature measurements and consider replacement. Besides automated start-up procedures, this is a prerequisite to assess admissible temperature limitations and to operate with less conservative set points.

8. **Improve the plant efficiency at part load and the dynamic behavior of the plant:**
   This refers to measures using the potential of the water-steam cycle – such as frequency support by condensate stop and HP heater optimization – as well as measures enhancing the performance of important equipment and components, e.g. ID, FD and PA fans or feed water pumps.

9. **Improve the coal quality:**
   The better the coal quality the better the combustion process. Therefore, measures to improve and to monitor coal quality should be considered, such as blending and washing as well as online coal analysis.

10. **Consider storage options to enhance the overall flexibility performance of the plant:**
    This refers to battery or thermal storage systems. The benefit of including storage technologies into the plant depends heavily on the market design.

1. About the toolbox

The flexible operation of coal-fired power plants requires suitable technologies, skilled people and leadership with foresight. In addition, it needs to be recognized that this new operating regime implies a change process that can only be managed successfully with a holistic approach.

Flexible operation needs a holistic approach

The tool box is designed to support the deployment of this change process in existing power plants by addressing the following questions:

- What procedures have proven successful for identifying and implementing flexibility measures?
- What are the proven technical measures to adapt existing plants to flexible operation?
- What are the consequences for the Operation & Maintenance (O&M) of the plant?
- What are the requirements for the personnel? Which training are useful?
- What are the tasks the plant management needs to address?

IT provides an overview of numerous proven measures, practical tips and recommendations for training as well as references for management issues. Therefore, it is divided into four sections – Retrofit, Operation & Maintenance, Training, and Management.

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Figure 1 Toolbox structure

The Instrumentation and Control (I&C) system plays a crucial role for flexible operation. Plant status transparency, the availability of operating data, sophisticated data assessments and advanced controls are a prerequisite for operating a power plant with enhanced flexibility. Moreover, the I&C system is the link joining all aspects important for efficient plant operation. It should be in the focus of any flexibility project as the benefits and the cost effectiveness are unbeatable. With respect to further digitization, I&C optimization offers even more potential, by enabling efficiency and flexibility enhancements at the same time.

The Toolbox was initiated under the auspices of the Indo-German Energy Forum. Therefore, it contains a special chapter about Indian specifics in the field of flexible operation of coal-fired power plants.

2. Introduction to flexible Power plant operation

2.1 Situation in Germany

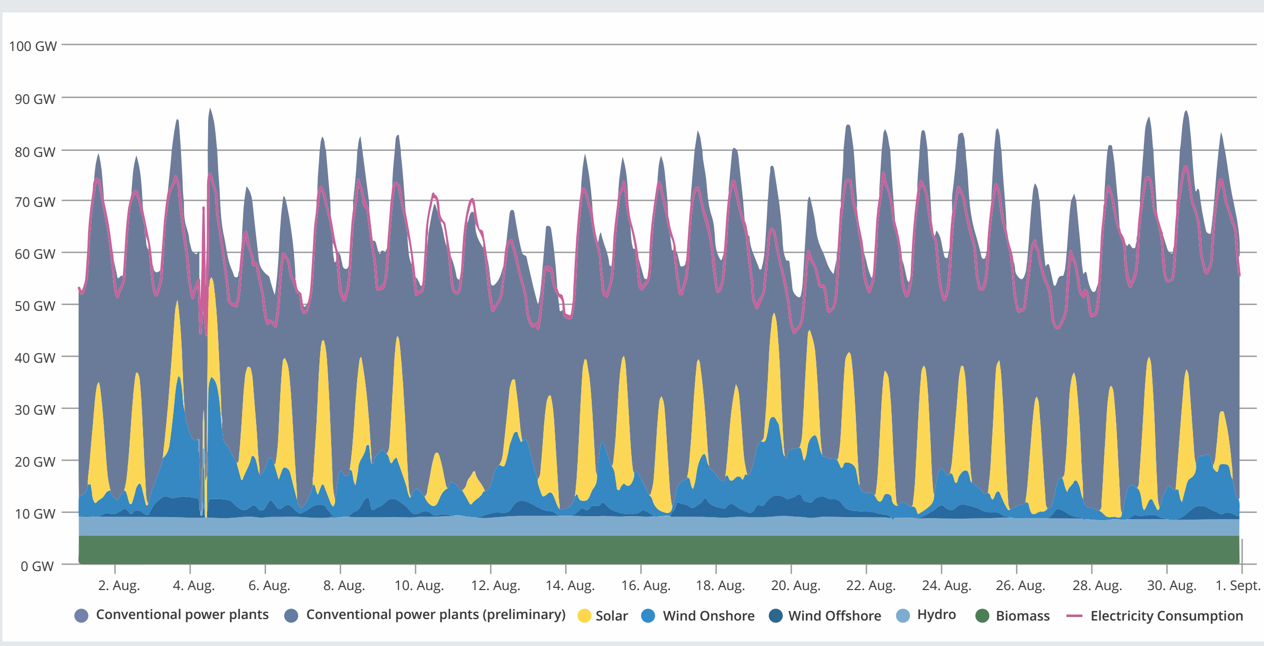
Renewables, with a share of almost 39% percent in electricity generation in 2017, are now the number one energy source in Germany. Political targets even envisage a renewables' share of 80 percent in primary energy consumption in 2050. Moreover, nuclear power plants will be phased out completely by 2022. An overview of the installed capacity is shown in.

Table 1 Overview of the installed capacity in Germany; in GW as of December 31, 2017

Total	Renewables				Thermal				Nuclear
	Solar	Wind	Hydro	Biomass	Gas	Diesel	Coal	Lignite	
203,22	42.98	56.19	5.60	7.39	29.50	4.44	25.05	21.29	10.8
	112.15				80.27				

The feed-in of fluctuating renewables, especially from solar and wind, is the normal situation in Germany. In periods with lots of sun and wind – as shown in – renewable energies are able to cover most electricity demand.

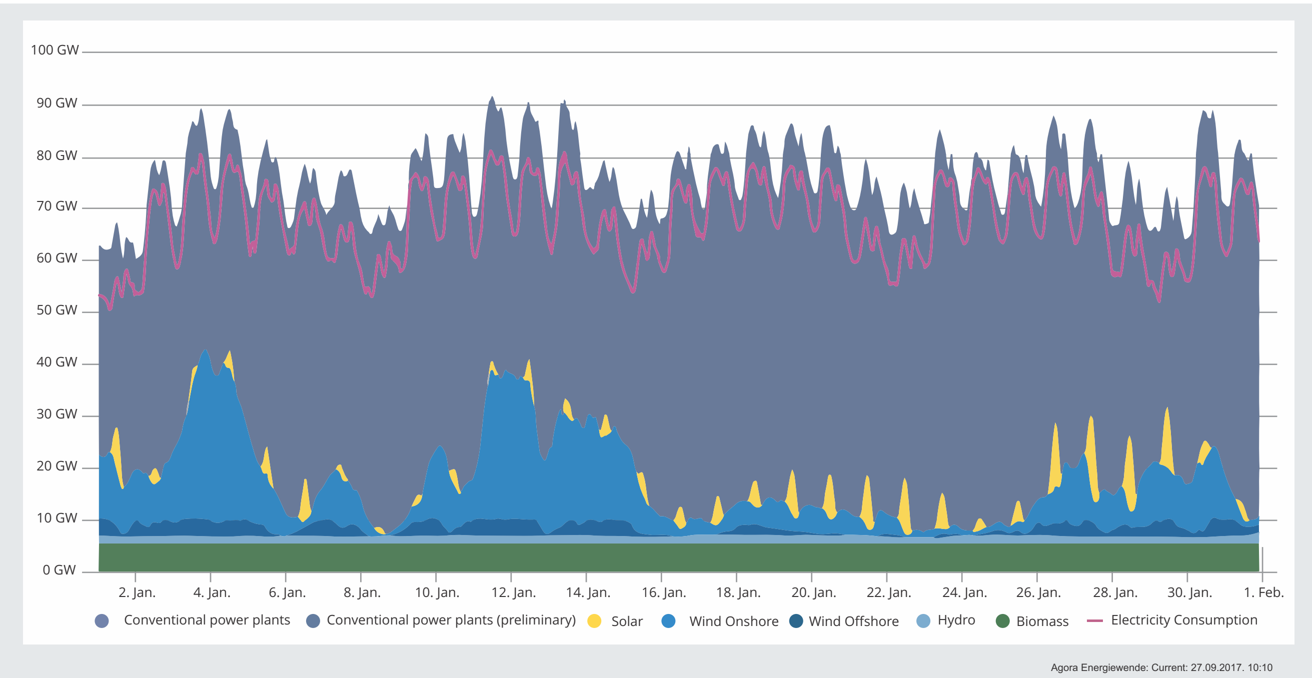
Figure 2 Electricity production in Germany in August 2017



Source: Agora Energiewende

However, there are also situations in which conventional power plants need to supply almost all demand, especially in winter when the sun is low (see Figure 3).

Figure 3 Electricity production in Germany in January 2017



Source: Agora Energiewende

Thus, the residual load has to remain very flexible so that it can cover all potential scenarios.

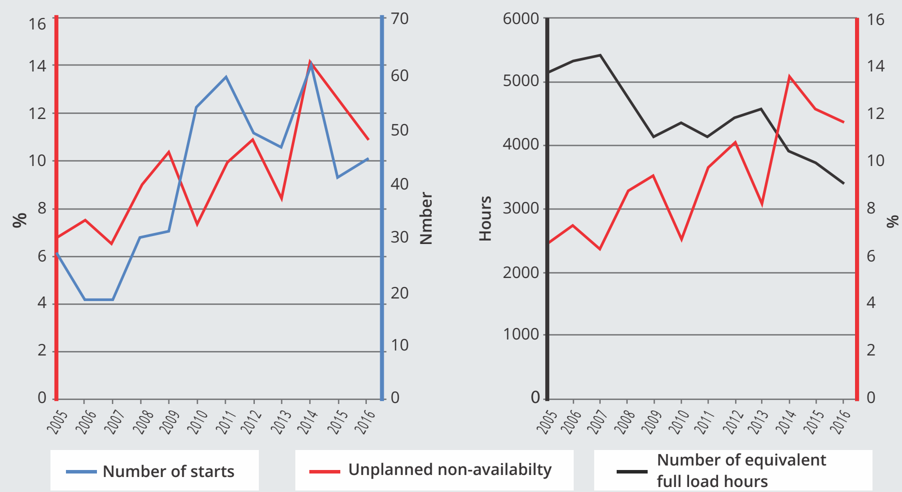
This new operating regime results in fewer annual operating hours, more starts and lower plant load factors. The following figures show the development of the unplanned unavailability, number of starts and number of equivalent full load operating hours for hard coal-fired power plants in Germany over ten years. The figures indicate a significant correlation between the number of starts, full load hours and unplanned unavailability, which has severely increased over this ten-year period. The trend is based on an analysis of the VGB database KISSY – Power Plant Information System.

The analysis led to the following conclusions:

- An aging that experientially leads to higher unavailability rates, especially when planned maintenance was reduced in the past.
- Flexible operation drifts away from the original design of plants, and consequently contributes to rising unavailability.

The comprehensive analysis and findings of the data assessment were published in an article of the Power Tech journal in September 2017.

Figure 4 KISSY analysis of 49 German hardcoal units > 200 MW, 2005 – 2016



Please note, that the values for "unplanned availability" differ slightly in the two graphs. The reason for this is that the number of plants considered for the "number of starts" assessment is different to the number of plants for the "number of equivalent full load hours" assessment.

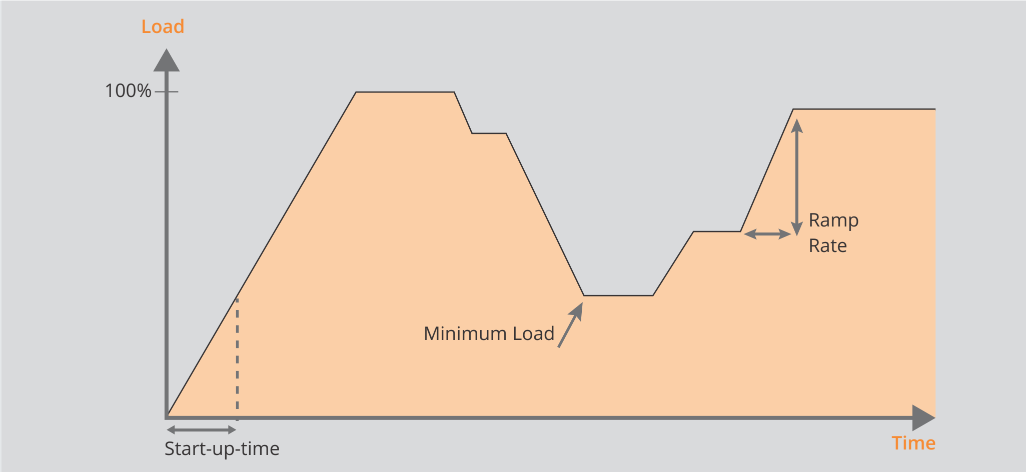
2.2 Technical flexibility parameters

From a technical perspective, flexible power plant operation comprises three different dimensions (see also):

Table 2 Overview of flexible power plant operation

Low minimum load	The minimum load represents the lowest load level at which the power plant operates under stable conditions and without supporting fuels, e.g. oil. A low minimum load operation reduces losses in low price hours and avoids shut-downs and respectively start-ups. Thus, start-up costs and lifetime consumption due to thermal stress can be reduced. Moreover, a low minimum load operation supports the grid operator – by providing rotary inertia – if plants remain synchronized. The minimum load operation entails significantly lower efficiencies.
Short and cost-effective start-up	Start-up time is defined as the time period between the start of power plant operation and stable minimum load being reached. Short start-up and shut-down times are beneficial, enabling a quick response to changing market requirements, e.g. in two shifting operation. The thermal stress connected to these procedures has the most severe impact on the lifetime consumption of components and equipment. Start-up times are classified as follows: ▪ Hot start: < 8 hours (h) ▪ Warm start: > 8 h and < 48 h ▪ Cold start: > 48 h Due to the increased number of start-ups (see), cost savings become increasingly important as well.
High ramp rates	The ramp rate indicates how fast a power plant can change its power output in a certain time. High ramp rates ensure a fast reaction to changed market conditions. Power plants with dynamic cycling abilities can participate in different markets (e.g. for ancillary services).

Figure 5 Dimensions of flexible power plant operation



The following table provides an overview of flexibility parameters in different types of thermal power plants. The different figures refer to usual, state-of-the-art and potential values.

Table 3 Flexibility parameters of thermal power plants; source: VDE and VGB

PLANT TYPE	COAL	LIGNITE	CCGT	GAS TURBINE
Load gradient [% / min]	2 / 4 / 6	2 / 4 / 6	4 / 8 / 12	8 / 12 / 15
in the load range [%]	40 to 90	50 to 90	40* to 90	40* to 90
Minimum load [%]	40 / 25 / 15	60 / 40 / 20	50 / 40 / 30*	50 / 40 / 20*
Ramp-up time for hot start [h]	3 / 2 / 1	6 / 4 / 2	1.5 / 1 / 0.5	< 0.1
Ramp-up time for cold start [h]	7 / 4 / 2	8 / 6 / 3	3 / 2 / 1	< 0.1

Usual value / state of the art / potential;*as per emission limits for NOx and CO; CCGT = Combined Cycle Gas Turbine

Gas turbine and combined cycle plants are faster and more agile than coal-fired power plants. Especially the start-up procedure of coal plants is much more complex. Thus, many measures described in this Toolbox are dedicated especially to coal-fired power plants.

2.3 Implementation of technical flexibility measures

In order to prepare an individual plant for flexible operation, several preliminary activities are required. This mainly involves analyzing the power plant using historic data as well as test runs providing an insight into the real performance of the plant with respect to minimum load, start-up time and ramp rates. These test runs are an indispensable step for achieving status quo transparency.

The further procedure is shown in the following figure. This implementation cycle comprises the following steps.

(1) **Analysis of the status quo** of the power plant using historic data including a definition of test runs.

(2) The second step refers to **test runs at the power plant.** The test program should comprise part load and minimum load operation, start-up test runs and cycling runs for a certain period.

(3) The information and data gathered in the course of the test runs form the basis for the **analysis of the plant's performance.**

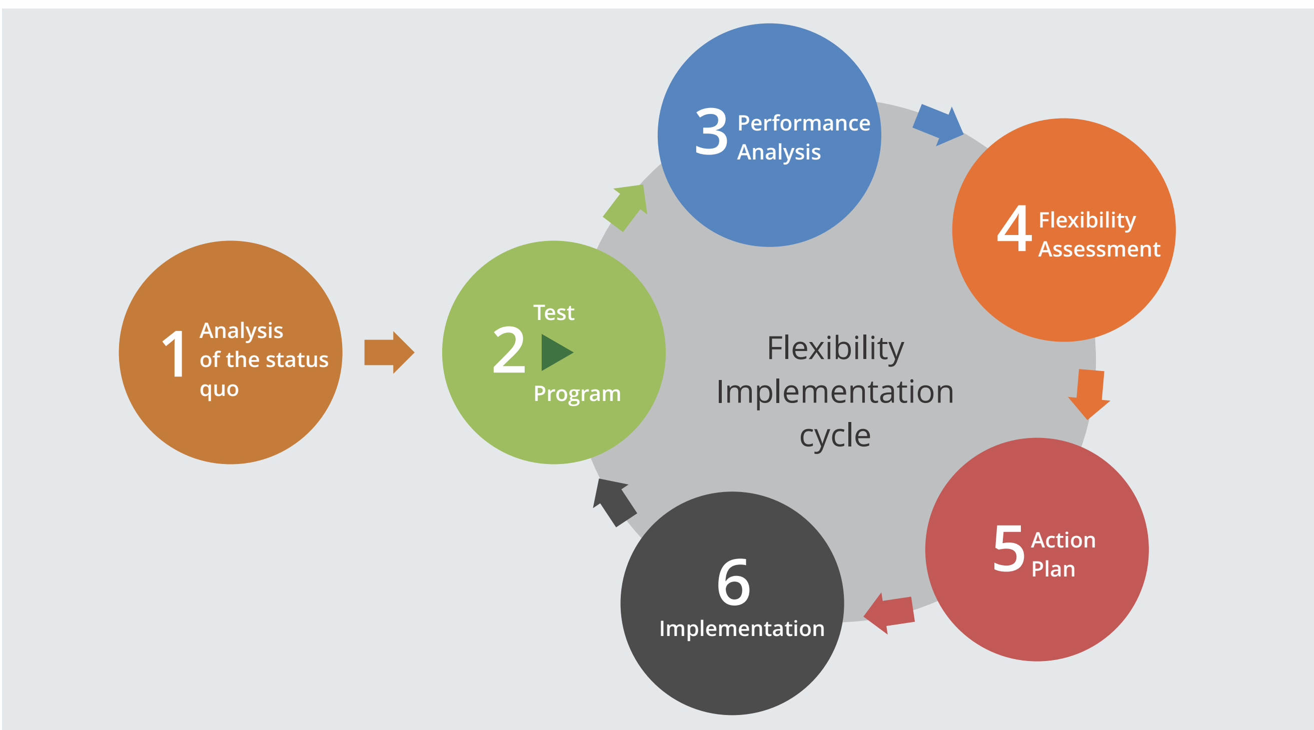
(4) Based on the performance analysis using test runs and the analysis of historic data, **measures for flexibility enhancement are determined and assessed based on a cost-benefit analysis.**

(5) **An action plan** can be developed based on the assessment of the flexibility measures.

(6) Finally, the **selected measures are to be implemented** at the plant site.

Then the cycle of evaluating and assessing plant performance with respect to the flexibility behavior can start again. Subsequent test runs specifically focus on fine-tuning the measures implemented. Consequently, step 1, 4 and 5 might be bypassed at this stage. By following this iterative approach, technical measures comprising retrofits and aligned O&M procedures can be successfully implemented.

Figure 6 Implementation cycle for technical flexibility measures

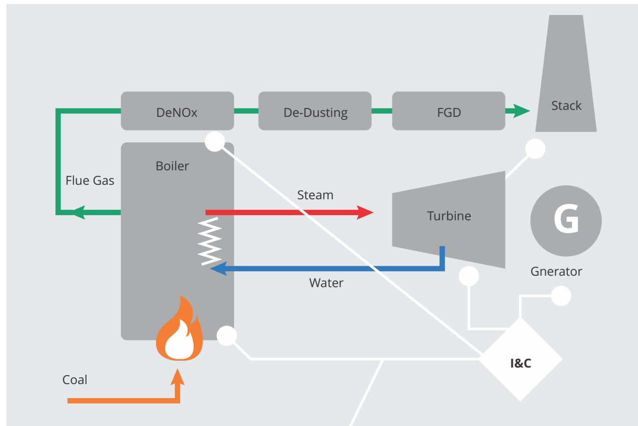


3. RETROFIT MEASURES ENHANCING FLEXIBILITY

Different flexibility enhancement measures that require a plant retrofit are presented in this chapter. The measures are assigned to different plant areas (see) and focus on:

- Combustion
- Water-steam cycle
- Turbine
- I&C system
- Auxiliary systems

Figure 7 Main areas of a coal-fired power plant



This document, in addition to the existing plant areas, also contains a section about common storage technologies. The description of each measure includes information about:

- Flexibility impact
- Limitations and critical issues that are addressed by the measure
- Description of the key features related to the measure
- Estimation of the required investment
  A < 100,000 USD,
  100,000 USD < B < 300,000 USD,
  300,000 USD < C < 600,000 USD,
  D >600,000 USD
- Time estimation for implementation
- Best practice example / references (if available)
- Note that provides an assessment of the measure's benefit

The **total investment** required for retrofit is very specific and depends on numerous aspects, such as:

- The actual plant status and its level of automation
- The market framework – incentives and business models rewarding flexibility
- Other contractual obligations, e.g. regarding power and/or heat supply

However, experience shows that an average investment of about **5 to 15 USD** per KW is required to enhance flexible operation – reducing the minimum load to 20 to 40 percent. These figures do not include the investment costs for storage technologies (chapter).

Further references for flexible thermal power plant operation can be found in the following studies and reports:

- Flexibility in thermal power plants, **Study of Agora Energiewende,** June 2017
- **Final Report** of the joint project "Partner Steam Power Plant", December 2016
- Increasing the flexibility of coal-fired power plants, IEA report 242, Colin Henderson, September 2014

In the following pages many proven measures are described according to the structure. Due to the nature of a toolbox the measures are described in a generic way. The aim of this chapter is to provide an overview of promising measures based on experience. If not stated within the tables, the measures might be an option for all types and sizes of power plants. However, the actual improvement potential and the costs and time line have to be investigated for each power plant individually. Only after a deeper analysis, a ranking of measures for the power plant considered is possible.

Independently of the flexibility options considered, the following measure is highly recommended in all cases.

GENERAL – EVALUATION OF PROCESS LIMITATIONS IN COOPERATION WITH OEM	
Flexibility impact	Minimum load reduction, start-up optimization, ramp rates
Limitations	General (in particular boiler and turbine)
Description	▪ Evaluation should include a boiler calculation to assess the influence of low load operation and the temperature and pressure gradients on boiler components and equipment ▪ An inventory review is required to assess the plant status in detail and to derive a schedule for test programs ▪ Establish transparency about the technical boundary conditions for flexible plant operation
Investment	A – B; depending on the OEM, no investment might be needed
Timeline	1 – 3 months
Best practices or references	N/A
Note	Precondition for further measures

3.1 Combustion

COAL STOCKYARD – THERMOGRAPHIC DETECTION SYSTEM AND COAL HANDLING	
Flexibility impact	Minimum load reduction
Limitations	Self-ignition of coal in coal stockyard
Description	▪ A reduction of the minimum load together with more frequent operation in minimum load leads to an increased storage period of coal that favors self-ignition ▪ Besides installing a detection system, appropriate coal handling in the stockyard (compaction) is recommended to avoid self-ignition
Investment	A – B and additional O&M costs
Timeline	1 – 3 months

Best practices or references	▪ Nolte M.; Brüggendick, H. and Brosch, K.: Kohlekraftwerke im Energiemix mit den erneuerbaren Energien – Der Schwachlastbetrieb und seine Auswirkungen auf das Kohlekraftwerk. Kraftwerkstechnik – Sichere und nachhaltige Energieversorgung – Band 3, TK-Verlag, 2011, pp. 699-707 ▪ Carpenter, A.M.: Management of coal stockpiles, IEA Coal Research 1999, ISBN 92-9029-333-0
Note	This measure does not improve the flexibility of a power plant but covers a secondary effect which needs to be taken into account when operating the power plant in a more flexible way.

FUEL SUPPLY – ONLINE COAL ANALYSIS	
Flexibility impact	Minimum load reduction, start-up optimization, ramp rates
Limitations	Flame stability, reproducibility of heat output
Description	▪ A general requirement for flexible operation is the provision of coal of a sufficient quality ▪ By using an online coal analysis, flame stability and reliable operation can be continuously maintained, leading to fewer trips and faster response times, for example
Investment	C
Timeline	6 – 12 months
Best practices or references	▪ Sloss, LL.: Blending of coals to meet power station requirements, IEA Clean Coal Center, July 2014, ISBN 978-92-9029-559-4 ▪ Lockwood,T.: Advanced sensors and smart controls for coal-fired power plant, IEA Clean Coal Centre, June 2015, ISBN 978-92-9029-573-0 ▪ Reid, I.: Coal Beneficiation, IEA Clean Coal Centre, June 2017, ISBN 978-92-9029-600-3
Note	As long as the provision of coal with a sufficient quality cannot be maintained, this measure is to be seen as precondition for further measures like e.g. one mill operation due to ensuring a more reliable and reproducible operation.

FUEL SUPPLY – HOT GAS GENERATOR	
Flexibility impact	Start-up optimization, minimum load reduction.
Limitations	Coal drying, starting condition of mill
Description	▪ To guarantee the sufficient drying of coal, hot air is required. If the hot air comes from the air pre-heater, the entire system (boiler and flue gas path) has to be warmed-up using start-up fuel ▪ The hot gas generator is capable of providing sufficient primary air temperature almost instantaneously. Consequently, the coal mills can be started earlier, leading to cost savings by allowing expensive start-up fuel to be substituted earlier ▪ Particularly effective for lignite-fired power plants that require recirculated flue gas for coal drying ▪ Drying extremely wet coal, caused by heavy rainfall, as well as drying coal that is out of the range from worse coal as specified for the grinding process ▪ The hot gas generator can be used to keep the required flue gas temperatures in order not to adversely affect flue gas cleaning equipment as well as avoiding flue gas temperatures falling below dew point of SO3 in particular at the cold end of the air pre-heater
Investment	D
Timeline	6 – 12 months
Best practices or references	▪ European Patent 12 162 930 ▪ German power plants Bexbach / Weiher and Herne unit 4
Note	This measure allows for using coal which has a higher moisture compared to the design coal improving the fuel flexibility. In addition, this measure has a medium improvement potential with respect to reducing start-up costs and minimum load.

FUEL SUPPLY AND FLUE GAS PATH – STEAM COIL AIR PRE-HEATER	
Flexibility impact	Minimum load reduction, start-up optimization
Limitations	Coal drying, flue gas temperatures, dew points
Description	▪ To guarantee a sufficient drying of coal, hot air is required. If the hot air comes for the air pre-heater, the entire system (boiler and flue gas path) first has to be warmed-up using start-up fuel (see alternatively hot gas generator) ▪ The steam coil air pre-heater is capable of supporting the provision of the primary air temperature required during start-up in particular if an auxiliary boiler exists, since sufficient steam parameters are required for activating the steam coil pre-heater. Consequently, the coal mills can be started earlier leading to cost savings by allowing for earlier substitution of expensive start-up fuel ▪ The steam coil air pre-heater can be used to keep the required flue gas temperatures in order not to adversely affect flue gas cleaning equipment as well as avoiding flue gas temperatures falling below dew point of SO3 in particular at the cold end of the air pre-heater ▪ Particularly effective for lignite-fired power plants requiring recirculated flue gas for coal drying
Investment	D; A – B if only recommissioning of existing hardware required
Timeline	6 – 12 months
Best practices or references	Standard design in German power plants
Note	This measure has a medium improvement potential with respect to flexibility reducing start-up costs and minimum load. It has to be synchronized with other fuel supply measures.

FUEL SUPPLY – ONLINE MANAGEMENT SYSTEM	
Flexibility impact	Minimum load reduction, start-up optimization
Limitations	Coal drying, flue gas temperatures, dew points
Description	▪ A general requirement for flexible operation is the provision of coal of sufficient quality ▪ An online pulverized coal and air distribution management system is capable of measuring the air-fuel ratio to coal burners in each PC pipe to coal burners in real time which can be optimized automatically based on the received coal quality ▪ Unequal distribution of carbon dust to burners is mitigated

Investment	B
Timeline	6 – 12 months
Best practices or references	German power plant Walsum unit 10
Note	As long as the provision of coal with a sufficient quality cannot be maintained, this measure is to be seen as precondition for further measures. Consequently, it might have high improvement potential with respect to flexibility

FUEL SUPPLY – INCREASED NUMBER OF MILLS	
Flexibility impact	Minimum load reduction, start-up optimization
Limitations	Minimum load of each mill
Description	The minimum load of a mill is restricted by e.g. ▪ Minimum primary air flow ▪ Minimum speed of coal feeder By reducing the load, the air-fuel ratio deteriorates leading to potential flame instability. By installing more but smaller mills, a significantly reduced minimum load can be reached with the same number of mills activated ▪ Saving potential related to start-ups is given, as the heat output coming from the mill can be reduced allowing an earlier transition from start-up flue to coal
Investment	D
Timeline	6 – 12 months
Best practices or references	Joint research project Partner Steam Power Plant for the renewable power generation funded by the German Federal Ministry for Economic Affairs and Energy
Note	This measure might have a high improvement potential with respect to flexibility but it also requires high investment for the existing power plant. Therefore, it is rather a measure to be considered for newly built power plants. Additionally, it has to be synchronizes with coal quality and corresponding measures.

FUEL SUPPLY – EXPLOITING THE STORAGE CAPABILITIES OF MILLS	
Flexibility impact	Ramp rates
Limitations	Slow response time of mill/boiler output
Description	▪ To get faster heat output, the storage capabilities of mills can be exploited by adapting the grinding pressure, purposely releasing or storing coal from/in the mill ▪ Response time improvement and storage capacity severely depends on mill type
Investment	B
Timeline	3 – 6 months
Best practices or references	▪ Kurth, M.; Greiner F.: Herausforderungen an die Kraftwerksleittechnik durch steigende dynamische Anforderungen an die Verfahrenstechnik. VGB PowerTech Journal 8/2008 ▪ Kallina, G.; Kochenburger, A.; Lausterer, G.: Wirtschaftliche Ertüchtigung von Kraftwerken zur Netzfrequenzstützung durch gestufte Speichernutzung. VGB Kraftwerkstechnik 2/2000 ▪ German power plants Voerde and Bexbach
Note	It can have a medium to high improvement potential with respect to increasing ramp rates with rather low investment. However, the real potential severely depends on the installed mills. In addition, the potential can be increased by using this measure together with the online fuel supply management system.

FUEL SUPPLY – DYNAMIC CLASSIFIER	
Flexibility impact	Ramp rates
Limitations	Slow response time of mill / boiler output
Description	▪ To get faster heat output the storage capabilities of mills can be exploited by purposely adapting the classifier's rotational speed ▪ A lower classifier rotational speed releases more coal dust to the burner whereas a higher speed separates more coal
Investment	D
Timeline	6 – 12 months
Best practices or references	German power plant Walsum unit 10
Note	This measure might have medium improvement potential with respect to flexibility.

FUEL SUPPLY – INDIRECT FIRING	
Flexibility impact	Start-up optimization, ramp rates
Limitations	Coal drying and grinding, heat output
Description	▪ An indirect firing system leads to a decoupling of coal mills and burners by storing pulverized coal dust ▪ The heat output reacts significantly faster than in the case of direct firing ▪ Further benefits are that the mills can always be operated at nominal load and it is possible to maintain a more uniform heat distribution in the furnace ▪ It is possible to install hybrid firing by direct and indirect firing
Investment	D
Timeline	6 – 12 months
Best practices or references	▪ Joint research project Partner Steam Power Plant for the renewable power generation funded by the German Federal Ministry for Economic affairs and Energy ▪ Ehmann, M.: Kohlenstaubbrenner zur Verfeuerung von in Dichtstromförderung zugeführtem Brennstoff. European Patent, EP2009351 ▪ Hybrid firing in power plants Niederaußem and Jänschwalde
Note	This measure has a high improvement potential with respect to increasing ramp rates. However, additional and adequate storage capacity has to be added for pulverized coal leading to an extensive an expansive investment. It has to be synchronized with other fuel supply measures.

FUEL SUPPLY – ONE-MILL OPERATION	
Flexibility impact	Minimum load reduction
Limitations	Flame stability
Description	▪ One-mill operation is a technical option that goes along with an optimized combustion process enabling minimum load of up to 15 percent by improving the air-fuel ratio ▪ Reliable equipment required for preserving availability requirements ▪ Generally an adaptation of the boiler protection system is required
Investment	B – D depending on requirements for (additional) hardware
Timeline	6 – 12 months

Best practices or references	▪ Lens, H. und M. Nolte, M.: Absenkung der Generatormindestlast von Steinkohlekraftwerken durch regelungstechnische und verfahrenstechnische Maßnahmen. VGB PowerTech Journal 4/2015 ▪ Heinzel, T.; Meiser, A.; Stamatelopoulos, G.-N. and Buck, P.: Implementation of Single Coal Mill Operation in the Power Plant Bexbach and Heilbronn Unit 7, VGB PowerTech Journal 11/2012 ▪ Stamatelopoulos, G.-N. and Heinzel, T.: Coal fired power plant Heilbronn Unit 7 – 750 MW – one-mill operation. PowerGen (2014) ▪ Several German power plants such as Altbach, Bexbach, Heilbronn unit 7, Weiher, Lünen
Note	This measure has a high improvement potential with respect to reducing the minimum load. However, the measure severely depends on coal quality and might require corresponding measures like adapting the boiler safety system. This measure is more adequate for hard-coal fired power plants.

COMBUSTION – RELIABLE FLAME DETECTION	
Flexibility impact	Minimum load reduction, start-up optimization
Limitations	Decreasing flame intensity
Description	Usually zonal flame detection becomes inappropriate at reduced minimum load. Thus, direct flame detection is to be recommended and, consequently, new sensors are to be installed at least for the burner levels active at reduced minimum load In addition, more reliable flame detection might allow for more reproducible start-ups
Investment	B – D depending on required replacements or modification of hardware
Timeline	6 – 12 months depending on modifications required
Best practices or references	▪ Heinzel, T.; Meiser, A.; Stamatelopoulos, G.-N. and Buck, P.: Implementation of Single Coal Mill Operation in the Power Plant Bexbach and Heilbronn Unit 7, VGB PowerTech Journal 11/2012 ▪ Stamatelopoulos, G.-N. and Heinzel, T.: Coal fired power plant Heilbronn Unit 7 – 750 MW – one-mill operation. PowerGen (2014) ▪ Several German power plants such as Bexbach and Heilbronn unit 7

Note	This measure is rather a precondition for further measures like, in particular, one mill operation. Hence, secondarily it might have medium to high improvement potential with respect to flexibility.

COMBUSTION – RELIABLE IGNITION	
Flexibility impact	Start-up optimization
Limitations	Malfunctioning of burners
Description	▪ Basic requirement for start-up optimization ▪ Unnecessary trips and waiting times can be avoided
Investment	A – D depending on required replacements or modification of hardware, O&M (cyclic start of burners)
Timeline	1 – 12 months depending on modifications required
Best practices or references	N/A
Note	This measure is rather a precondition for further measures like, in particular, start-up optimization. Hence, secondarily it might have medium to high improvement potential with respect to flexibility.

COMBUSTION – PLASMA IGNITION	
Flexibility impact	Start-up optimization
Limitations	Requirement of start-up / auxiliary fuel for ignition
Description	▪ Coal is ignited using hot plasma flow ▪ Significant cost saving potential by reducing / replacing the use of start-up / auxiliary fuel (depending on whether all burner levels or only specific burner levels will be equipped with electric ignition)
Investment	B – D depending on whether existing burners can be modified or need to be replaced
Timeline	3 – 12 months
Best practices or references	▪ Heimann, G.: Flexibilitätssteigerungen von Braunkohlekraftwerken, VGB PowerTech 4/2015 ▪ Heimann, G.: Erfolgreiche Installation und Inbetriebnahme einer Zünd- und Stützfeuerung mittels Trockenbraunkohlebrenner mit Plasmazündung, VGB PowerTech 7/2016 ▪ Dry lignite increases flexibility, BINE info
Note	This measure might have medium improvement potential with respect to saving auxiliary fuel.

COMBUSTION – ELECTRIC IGNITION	
Flexibility impact	Start-up optimization
Limitations	Requirement of start-up / auxiliary fuel for ignition
Description	▪ Coal is ignited using a hot burner nozzle solely heated by electric energy ▪ Significant cost saving potential by reducing / replacing the use of start-up / auxiliary fuel (depending on whether all burner levels or only specific burner levels will be equipped with electric ignition)
Investment	B – D depending on whether existing burners can be modified or need to be replaced. Generally, modification requires less effort / investment compared to plasma ignition
Timeline	3 – 12 months
Best practices or references	▪ Joint research project Partner Steam Power Plant for the renewable power generation funded by the German Federal Ministry for Economic Affairs and Energy ▪ Leisse, A.; Rehfeldt, S. and Meyer, D.: Das Zündverhalten fester, staubförmiger Brennstoffpartikel an heißen Oberflächen. VGB PowerTech (2014)
Note	This measure might have medium improvement potential with respect to saving auxiliary fuel.

3.2 Water-steam cycle

BOILER – DRAINABLE HEATING SURFACES	
Flexibility impact	Start-up optimization
Limitations	Thermal stress
Description	Non-drainable bends (e.g. platen type super-heaters) are limiting in particular with respect to cold start-ups due to condensed water in the lower parts. If condensate in the tubes cannot be drained, the temperature during the start-up process must increase slowly to avoid temperature shocks in the tubes
Investment	Modification is not possible for existing power plants. Therefore, should be considered for new-build power plants only
Timeline	N/A
Best practices or references	All German power plants
Note	This measure is only suited for newly built power plants.

BOILER – TILTING BURNERS	
Flexibility impact	Minimum load
Limitations	Steam temperatures
Description	▪ In minimum operation, the live steam temperature as well as the temperature of the reheated steam generally decreases ▪ Using tilting burners the position of the flame can be used to shift the heat transfer from the radiative heating surfaces to the convective heating surfaces, which is beneficial for keeping the temperatures in an acceptable range ▪ Moreover, a non-uniform heat transfer to convective heating surfaces due to streaking can be overcome (which might also be possible by properly adjusting the burner levels)
Investment	D
Timeline	6 – 12 months
Best practices or references	Joint research project Partner Steam Power Plant for the renewable power generation funded by the German Federal Ministry for Economic Affairs and Energy
Note	This measure might have high improvement potential with respect to flexibility.

BOILER – THINNER DESIGN OF THICK-WALLED COMPONENTS	
Flexibility impact	Start-up optimization, ramp rates
Limitations	Thermal stress
Description	▪ The wall thickness as well as the material of the respective components influences the admissible thermal stress ▪ A thinner design usually allows faster temperature transients ▪ Alternatively, alternative materials allow for an increased thermal stress
Investment	Modification is generally not possible for existing power plants. Therefore, should mainly be considered for new-build power plants only
Timeline	N/A
Best practices or references	Joint research project Partner Steam Power Plant for the renewable power generation funded by the German Federal Ministry for Economic Affairs and Energy
Note	This measure is only suited for newly built power plants.

BOILER – EXTERNAL HEATING OF THICK-WALLED COMPONENTS	
Flexibility impact	Start-up optimization
Limitations	Thermal stress
Description	▪ During start-up the thick-walled components (e.g. drum, start-up vessel, headers) are the limiting factor for increasing the firing rate ▪ Using external heating thermal stress can be mitigated allowing faster start-up times
Investment	N/A
Timeline	N/A
Best practices or references	Hentschel, J.; Zindler, H.; Prabucki, M.-H.; Spliethoff, H. and Amm, D.: Optimierung eines konventionellen Kraftwerksanfahrprozesses durch Beheizung dickwandiger Bauteile. Kraftwerkstechnik 2014, Freiberg, Saxonia, 2014
Note	This measure might have low to medium improvement potential with respect to flexibility.

BOILER – RECIRCULATION PUMP	
Flexibility impact	Minimum load reduction, start-up optimization
Limitations	Waste of energy – inefficient operation
Description	▪ Does not fit to drum-type boilers ▪ The minimum flow of a once-through boiler is about 40% of the nominal flow. To avoid unnecessary loss of energy and demineralized water via steam to the atmosphere, an adequate start-up and low load installation has to be provided, e.g. recirculation pumps from the start-up vessel to the economizer or evaporator. This measure is inevitable if a minimum load is envisaged where the unit is continuously driven in wet state ▪ Impermissible vaporization in the economizer caused by changeover to circulation mode in low load (increased water temperature at ECO inlet caused by water-recirculation) needs to be avoided ▪ The switching from once-through operation to circulation operation leads to temperature changes increasing the thermal stress of thick-walled components ▪ Another start-up and low load installation could be a start-up flash vessel, connected with the steam side to the cold reheat inlet and the water to the feed water tank. This measure is less efficient but has significantly less investment costs

Investment	D
Timeline	6 – 12 months
Best practices or references	Standard design for most German power plants
Note	This measure is not suited for power plants with drum-type boilers. It might have medium to high improvement potential by enabling the economic operation in reduced minimum load.

STEAM – HP BYPASS	
Flexibility impact	Start-up optimization
Limitations	Thermal stress
Description	▪ If no HP bypass is installed, the start-up uses existing drains and vents. The benefit of the HP bypass is to guarantee a sufficient cooling of the re-heater as long as the turbine is not in operation ▪ In order not to waste steam unnecessarily, proper control of the HP bypass is required (see I&C section)
Investment	Modification is generally extremely extensive for existing power plants. Therefore, should mainly be considered for new-build power plants only
Timeline	N/A
Best practices or references	Standard design for most German power plants
Note	This measure is rather suited for newly built power plants.

ECONOMIZER BYPASS	
Flexibility impact	Minimum load reduction
Limitations	Flue gas temperatures
Description	▪ To maintain required flue gas temperatures, feed-water can be forwarded to the evaporator using an economizer bypass so that the flue gas temperature at eco outlet increases. Consequently, it can be avoided that the flue gas cleaning equipment is adversely affected and that flue gas temperatures fall below dew point of SO3 in particular at the cold end of the air pre-heater ▪ Vaporization in the economizer needs to be avoided ▪ Only for power plants with DeNOx technologies

Investment	C – D
Timeline	6 – 12 months
Best practices or references	▪ Michels, B. and Kotzan, H.: Retrofit of an ECO bypass to reduce minimum load of a 750 MW hard coal-fired power plant, VGB PowerTech (2015) ▪ German power plant Mehrum unit 3
Note	This measure is in particular attractive for power plants with DeNOx technologies.

3.3 Turbine

LP BLADE REPLACEMENT	
Flexibility impact	Increase resistance against ventilation and water droplet erosion at low load operation
Limitations	Minimum steam flow
Description	Replacement of blades at the last LP stage as well as installation of shroud elements
Investment	C-D
Timeline	6 months
Best practices or references	Heddoun, H.; Richard, J.-M., VGB PowerTech Journal, 3/2017
Note	This measure might have low to medium improvement potential with respect to flexibility

MATERIAL SUBSTITUTION AND DESIGN MODIFICATION AT THE ROTOR	
Flexibility impact	Improve dynamic behavior of the turbine and shorten start-up time
Limitations	Plant performance and design standards
Description	▪ Replacement of the monoblock with a welded rotor consisting of two smaller rotor forgings including a cavity ▪ Applying 10% Cr-steel when considering the boiler code/standard or material as admitted per boiler code/standard
Investment	D
Timeline	At least 6 months
Best practices or references	Rediess, M. et.al, VGB PowerTech Journal, 3/2017

Note	The measure might have medium improvement potential with respect to flexibility

SUBSTITUTION OF THICK-WALLED COMPONENTS	
Flexibility impact	Improve dynamic behavior of the turbine and shorten start-up time
Limitations	Plant performance and design standards
Description	Using shrink rings or circumferential housing flanges to bolt inner HP casing to substitute thick-walled components by considering the boiler code/standard or material as admitted per boiler code/standard
Investment	C – D
Timeline	At least 6 months
Best practices or references	Rediess, M. et.al, VGB PowerTech Journal, 3/2017
Note	This measure is rather suited for newly built power plants.

HP STAGE BYPASS	
Flexibility impact	Improve dynamic behavior and the ability to provide frequency support
Limitations	Design and performance
Description	This permits additional HP steam to be admitted to the HP turbine some stages after the first blade row when the bypass valve is opened, also to give full arc admission at that stage. The system is normally designed to give a short-term 5% increase in power. It is however possible to design such systems for an additional 10% or even 15% increase in power, if required.
Investment	D
Timeline	6 – 12 months
Best practices or references	Colin Henderson: Increasing the flexibility of coal fired power plants, IEA Clean Coal Centre 242 (2014), ISBN 978–92–9029–564-8
Note	Measure to provide frequency control support

HEATING BLANKETS	
Flexibility impact	Start-up optimization
Limitations	Heat losses after shut-down
Description	Keep turbine warm during stand-stills by balancing the upper and lower casing and thus avoiding the bending of the shell
Investment	B
Timeline	1 month
Best practices or references	Biesinger, F. et.al, VGB PowerTech Journal, 11/2016
Note	Might have low improvement potential with respect to flexibility.

3.4 I & C systems

RELIABLE TEMPERATURE MEASUREMENTS	
Flexibility impact	Start-up optimization, ramp rates
Limitations	Thermal stress
Description	▪ Accurate and well-placed temperature measurements of thick-walled components (inner wall and middle wall) are inevitable for evaluating the thermal stress (temperature difference) during power plant start-up and shut-down and the corresponding lifetime consumption ▪ Measured temperatures directly affect the firing rate
Investment	N/A depending on power plant condition
Timeline	N/A depending on power plant condition
Best practices or references	▪ Lens, H.: Optimierung des Anfahrvorgangs eines Steinkohlekraftwerks,“ in Kraftwerkstechnik, Freiberg, Saxonia, 2014, pp. 231-241 ▪ Lens, H.: Mid-Load Operation of Large Coal-Fired Power Plants, PowerGen Europe, 2014 ▪ TÜV Rheinland and operator RWE Power launch novel sensor system for permanent monitoring of high-duty thick-walled components in power plants
Note	This measure is to be considered as a precondition for other measures.

ACCURATE AND RELIABLE CONTROL OF START-UP FUEL	
Flexibility impact	Start-up optimization
Limitations	Thermal stress of thick-walled components
Description	▪ Mass flow of start-up fuel needs to be accurately controlled to allow a gentle and reproducible start-up ▪ Proper actuation (flow control valves) and measurements (flow measurements) required
Investment	N/A depending on hardware installed
Timeline	N/A depending on hardware installed
Best practices or references	Standard design for German power plants
Note	This measure is to be considered as a precondition for other measures.

MODEL-BASED THERMAL STRESS CALCULATOR	
Flexibility impact	Start-up optimization, ramp rates
Limitations	Thermal stress
Description	▪ Using a dynamical wall model with physical parameters, e.g. for heat transfer and heat distribution, it is possible to compute the temperature difference from the steam temperature, which usually is measured anyway ▪ The available margin with respect to thermal stress can be used as a feedback signal for the start-up controller to keep the temperature difference in its admissible range ▪ Less conservative than measuring the temperature difference using traditional measurements
Investment	B
Timeline	12 months depending on number of start-ups available
Best practices or references	▪ Lens, H.: Optimierung des Anfahrvorgangs eines Steinkohlekraftwerks. In Kraftwerkstechnik, Freiberg, Germany, 2014, pp. 231-241. ▪ Lens, H.: Mid-Load Operation of Large Coal-Fired Power Plants, PowerGen Europe, 2014 ▪ Wagner. J. and Deeskow, P.: Trend prognosis and online diagnostics of thick walled boiler components for a flexible mode of operation. In Proceedings of the ASME 2014 Pressure Vessels & Piping Conference, Anaheim, California, USA, July 20–24, 2014.

	▪ Kallina, G.: Vorausschauender Freilastrechner für das optimale Anfahren von Dampferzeugern. In VGB Kraftwerkstechnik 75 (1995). ▪ Energietechnische Gesellschaft im VDE (ETG): Erneuerbare Energie braucht flexible Kraftwerke – Szenarien bis 2020, Gesamttext. VDE (2012) ▪ DIN EN 12952-3: Water-tube boilers and auxiliary installations – Part 3: Design and calculation for pressure parts of the boiler (2012) ▪ Several German power plants, e.g. Voerde A/B, West 1/2, GKM unit 9
Note	This measure might have a medium improvement potential with respect to flexibility.

ADAPTATION OF MEASUREMENTS RANGES	
Flexibility impact	Minimum load reduction
Limitations	Measurements ranges
Description	▪ Measurement range might not be sufficient for reduced minimum load, in particular with respect to pressure, temperature and flow ▪ The quality of flow measurements usually deteriorates at the lower limit of the measurement range, potentially adversely affecting the corresponding control
Investment	N/A depending on hardware installed
Timeline	N/A depending on hardware installed
Best practices or references	N/A
Note	This measure is to be considered as a precondition for other measures.

AUTOMATIC START-UP PROGRAM (ONE BUTTON START-UP)	
Flexibility impact	Start-up optimization
Limitations	N/A
Description	▪ An automatic start-up sequence lights off burners automatically, rolls the turbine as soon as the necessary conditions are reached and realizes a smooth transition between the particular start-up phases in order to avoid unnecessary waiting times ▪ Automated start-up is only possible once all relevant drains and vents are automated

Investment	A – C depending on current control implementation
Timeline	3 – 6 months
Best practices or references	Several power plants in Germany, e.g. power plant Voerde unit A/B, power plant Herne unit 4
Note	This measure might have a medium to high improvement potential with respect to flexibility In terms of guaranteeing reproducible start-ups.

START-UP OPTIMIZATION (FIRING RATE, HP BYPASS)	
Flexibility impact	Start-up optimization
Limitations	Thermal stress of thick-walled components
Description	▪ Mass flow of start-up fuel needs to be accurately controlled to allow a gentle and reproducible start-up ▪ Proper actuation (flow control valves) and measurements (flow measurements) required ▪ Proper degree of automation (sequential controls) required
Investment	Depending on degree of automation and hardware installed
Timeline	Depending on degree of automation and hardware installed
Best practices or references	▪ Lens, H.: Optimierung des Anfahrvorgangs eines Steinkohlekraftwerks. In Kraftwerkstechnik, Freiberg, Saxonia, 2014, pp. 231-241. ▪ Kallina, G.: Vorausschauender Freilastrechner für das optimale Anfahren von Dampferzeugern. In Kraftwerkstechnik 75 (1995). ▪ German power plants West 1/2, GKM unit 9
Note	This measure might have a medium to high improvement potential with respect to reducing start-up cost in particular by severely reducing the position of the HP bypass during start-up. Consequently, this measure primarily concerns power plants with HP bypass.

OPTIMIZATION OF UNDERLYING CONTROL LOOPS	
Flexibility impact	Start-up optimization, minimum load reduction, ramp rates
Limitations	Smooth process behavior, thermal stress
Description	Properly working underlying control loops are inevitable for realizing power plant flexibilization using advanced process control solutions. In general, these control loops are intensively commissioned only at nominal load so that the performance of these control loops deteriorates at new operating points (e.g. reduced minimum load).

	Moreover, flexible operation increasingly focuses on the dynamic behavior of the process rather than the stationary behavior leading to new requirements for existing control loops. Control loops to be considered are: ▪ Spray water control ▪ Feed-water control ▪ Enthalpy control ▪ Drum level control ▪ O_2 / air control ▪ Circulation control
Investment	C
Timeline	6 – 12 months
Best practices or references	▪ Kurth, M.; Greiner F.: Herausforderungen an die Kraftwerksleittechnik durch steigende dynamische Anforderungen an die Verfahrenstechnik, VGB PowerTech Journal 8/2008 ▪ Lens, H.: Optimierung des Anfahrvorgangs eines Steinkohlekraftwerks. In Kraftwerkstechnik, Freiberg, Saxonia, 2014, pp. 231-241 ▪ Several German power plants: Herne unit 4, Walsum units 9 / 10, GKM
Note	This measure should be generally taken into account and is a fundamental prerequisite for all three flexibility improvements particularly for start-up optimization and advanced unit control. The measure itself might even have low to medium improvement potential.

ADVANCED UNIT CONTROL	
Flexibility impact	Minimum load reduction, ramp rates
Limitations	Smooth process behavior
Description	▪ Advanced unit control particularly comprises feed-forward model-based approaches that have proven to be an appropriate measure for improving the dynamic behavior of power plants ▪ Simulation environments can be used to support the commissioning by reducing the time needed for online optimization of relevant parameters
Investment	B – C
Timeline	6 – 12 months

Best practices or references	▪ W. Zehtner, W. and Schöner, P.:Erhöhung der Flexibilität von modernen Kohlekraftwerken durch Prozesssimulation. VGB-Workshop Kraftwerksflexibilisierung (2014) ▪ Meinke S.: Modellierung thermischer Kraftwerke vor dem Hintergrund steigender Dynamikanforderungen aufgrund der zunehmenden Windenergie- und Photovoltaikeinspeisung. Dissertation Universität Rostock, 2012 ▪ Richter, M.; Möllenbruck, F.; Obermüller, F.; Knaut, A.; Weiser, F.; Lens, H. and Lehmann, D.: Flexibilization of steam power plants as partners for renewable energy systems. 19th Power Systems Computation Conference (2016) ▪ Several German power plants
Note	This measure might have medium to high improvement potential with respect to flexibility – it strongly depends on the condition of the underlying control loops.

INDIRECT AND DIRECT THROTTLING OF EXTRACTION STEAM – ADVANCED FREQUENCY CONTROL	
Flexibility impact	Ramp rates (and ancillary services)
Limitations	Step response of load output
Description	In order to get a faster load change indirect and direct throttling of extraction steam can be applied: ▪ Condensate throttling (indirect) ▪ Throttling of extraction steam to LP preheaters and feed-water tank (direct) ▪ Throttling of extraction steam to HP pre-heater (direct) The coordination of the resulting inherent storage capacities can be used for advanced frequency control.
Investment	C
Timeline	6 – 12 months
Best practices or references	▪ Kurth, M.; Greiner F.: Herausforderungen an die Kraftwerksleittechnik durch steigende dynamische Anforderungen an die Verfahrenstechnik, VGB PowerTech Journal 8/2008 ▪ Kallina, G.; Kochenburger, A.; Lausterer, G.: Wirtschaftliche Ertüchtigung von Kraftwerken zur Netzfrequenzstützung durch gestufte Speichernutzung. VGB Kraftwerkstechnik 2/2000 ▪ German Patent DE 10 2005 034 847, Prinz, S. and Schreiber, W.: Einbau einer schnell schließenden Drehregelklappe ▪ Used in several German power plants for the provision of frequency control

Note	This measure has a medium to high improvement potential for increasing ramp rate and, alternatively, it can be used to increase the power plant efficiency by replacing the throttling of turbine valves for frequency control.

GENERAL – CONDITION MONITORING SYSTEM	
Flexibility impact	General
Limitations	Malfunctioning of equipment
Description	▪ Condition monitoring systems should monitor highly loaded boiler and piping components against creep and fatigue ▪ The systems should monitor the temperature differences and pressure, and signal when allowable limits are exceeded during the load changes. It would be advantageous if the monitoring systems have the what-if capability to calculate the impact of different start-up and shut-down scenarios on fatigue consumption
Investment	B – C
Timeline	3 – 4 months
Best practices or references	Sophisticated condition monitoring systems are used in many German power plants
Note	This measure might have low to medium improvement potential with respect to flexibility. This measure rather aims at reducing long-term O&M costs.

FEM ANALYSIS	
Flexibility impact	Start-up optimization
Limitations	Thermal stress
Description	With FEM analysis and a proper evaluation, admissible temperature differences can be increased leading to further potential for speeding up the start-up process (e.g. Ansys Workbench 17.0) The following plant data are required to execute the FEM calculations: ▪ Dimensions/geometry for the interconnections ▪ Material data ▪ Operating conditions (pressure and temperature) ▪ Definition of model transients for the calculations (e.g. 7 K/min, 14 K/min and 55 K/min) ▪ Definition of heat transfer coefficients (typically 1,000 and 3,000 W/(m²K) as model values from the DIN EN norms)

Investment	A
Timeline	1 – 3 months
Best practices or references	N/A
Note	This measure might have a medium improvement potential with respect to start-ups.

3.5 Auxiliary equipment

REPLACEMENT OF ACTUATORS AND FANS	
Flexibility impact	Start-up optimization, ramp rates, minimum load reduction
Limitations	Malfunctioning of equipment
Description	▪ Reliable actuators (fans, pumps, valves) are a basic requirement for optimized start-ups ▪ Unnecessary trips and waiting times can be avoided ▪ Actuators might not be fast enough to fulfill the more involved requirements of flexible operation ▪ The use of converter-driven fans and actuators enables speed control and thereby a fast reaction time and enhanced dynamics in a broad operation range
Investment	C – D; depending on hardware to be replaced
Timeline	Depending on hardware to be replaced
Best practices or references	Provided by many manufacturers, standard technology
Note	This measure should be considered as a precondition for other flexibility measures.

INSTALLATION OF DAMPERS IN AIR AND FLUE GAS DUCTS	
Flexibility impact	Start-up optimization
Limitations	Heat losses after shut-down
Description	Keeping the boiler warm by installing dampers: ▪ In the primary and secondary air duct ▪ In flue gas ducts ▪ In the Primary Air Cooler (PAC) ▪ Extends the warm start capability period to approx. 60 hours
Investment	D
Timeline	3 to 6 months

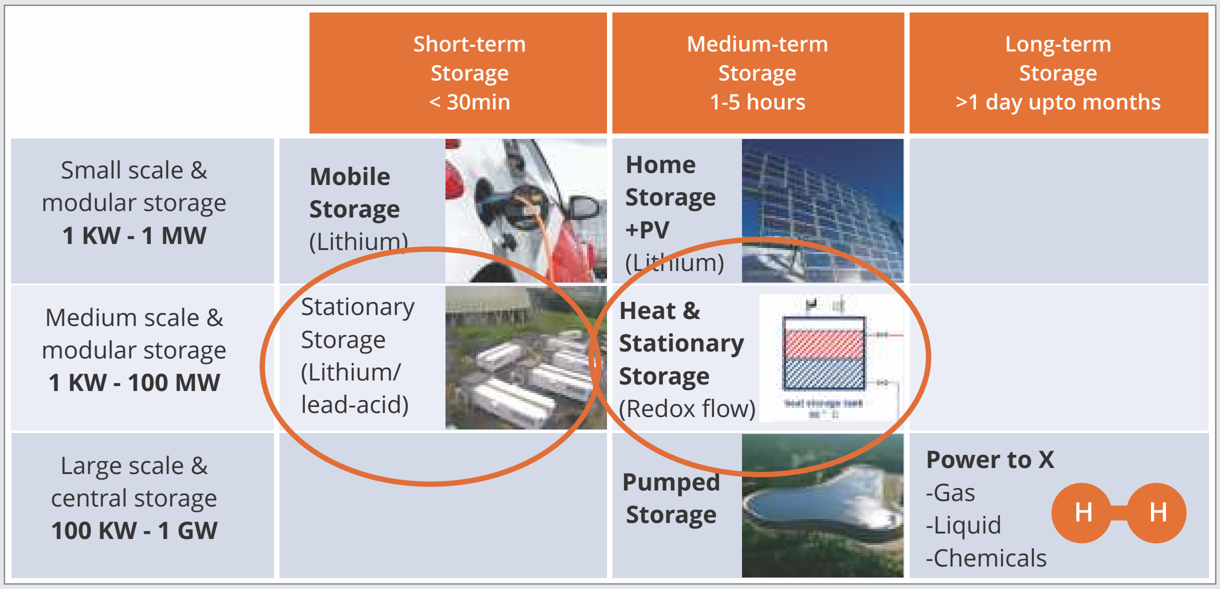
Best practices or references	Boewe, J. and Gade, U.: Power Plant Moorburg, Presentation at the VGB Congress 2016
Note	This measure might have low to medium improvement potential with respect to flexibility.

GENERATOR COOLING TECHNOLOGY	
Flexibility impact	Start-up optimization, ramp rates
Limitations	Thermal stress at generator windings
Description	▪ Adjustment of cooling technologies ▪ Water-cooled stator windings are more robust against thermal stress
Investment	N/A
Timeline	N/A
Best practices or references	▪ Weidner, J. R., VGB PowerTech Journal, 12/2016 ▪ Baca, M., Joswig, A., VGB PowerTech Journal, 6/2016 ▪ Wittner, S. et al., VGB PowerTech Journal, 8/2015
Note	This is a measure to mitigate the effects of cycling power plant operation.

3.6 Storage technologies

The use of storage technologies provides additional opportunities for enhancing power plant flexibility. The following figure shows the different storage options, already applied today. The storage options distinguish themselves by the scale and duration of storage.

Figure 8 Overview of storage technologies



Source: VGB based on Prof. Sauer, RWTH Aachen

The heat and stationary battery storage (circled in) are storage technologies that are directly applied in connection with thermal power plants.

Stationary battery storage

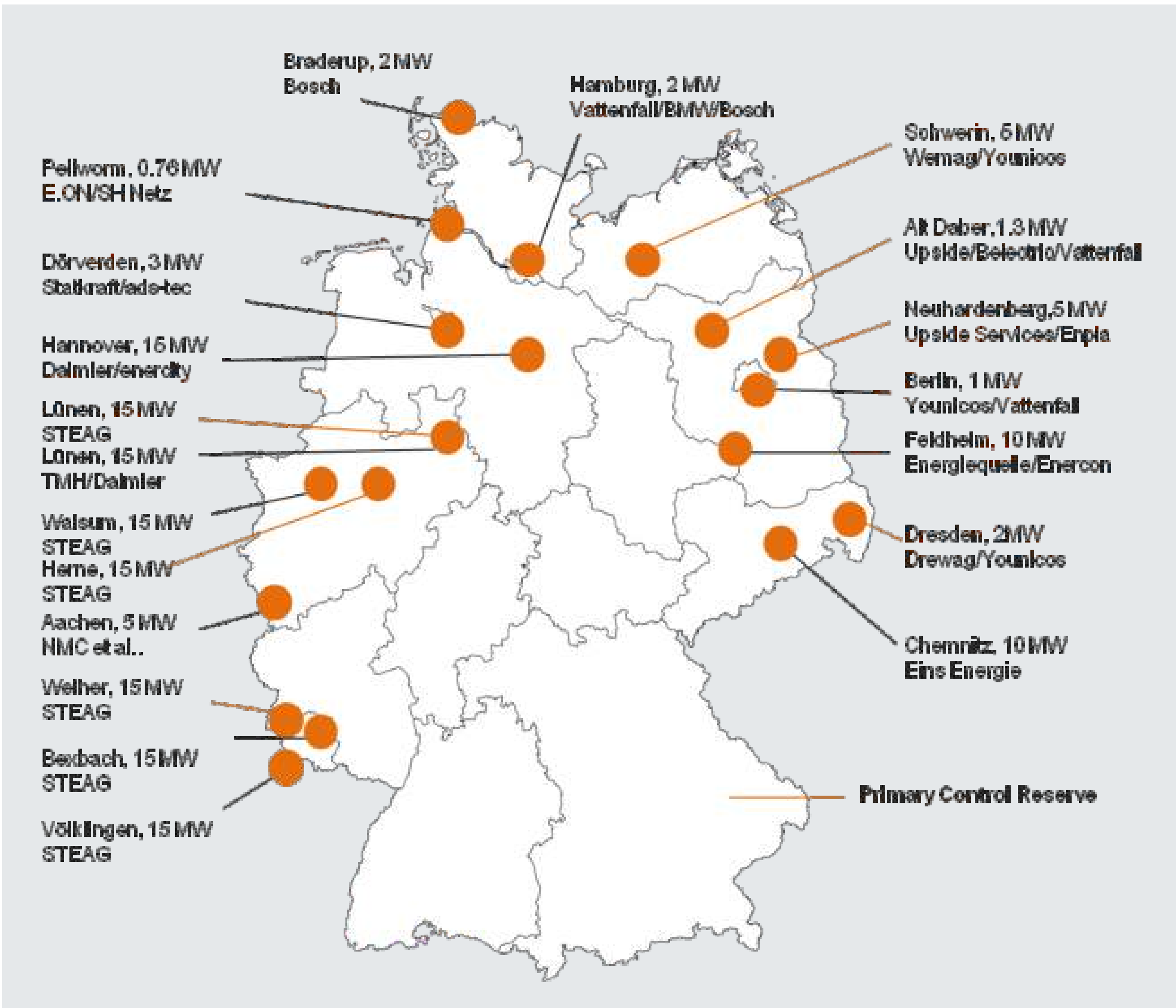
The main technology is a Lithium Ion (Li-Ion) battery system based on electrochemical charge / discharge reactions that occur between a positive electrode (cathode) that contains some lithiated metal oxide and a negative electrode (anode) that is made of carbon material or intercalation compounds. The electrodes are separated by porous polymeric materials allowing electron and ionic flow between each other and are immersed in an electrolyte that is made up of lithium dissolved in organic liquids.

When the battery is being charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge.

In 2015, more than 500MW of stationary Li-Ion batteries were operating worldwide in grid-connected installations. Systems in association with distributed renewable generators from a few kW to several MW, as well as for grid support with voltages up to 1kV have been designed and successfully tested. Whereas early systems were implemented for demonstration purposes, now such applications are being commercially developed in different regions of the world.

REF 4: www.ease-storage.eu/energy-storage/technologies/
Figure 9 shows all stationary battery systems installed in Germany.

Figure 9 Overview of battery storage parks in Germany as of Nov 2016;



Source: Büro F

STATIONARY LITHIUM BATTERIES	
Flexibility impact	Enhancing dynamic behavior
Limitations	Market options for primary control and other ancillary services
Description	Battery systems are able to absorb energy from, or feed energy into, the grid within a few seconds up to at least 30 minutes. Owing to this, they are particularly well suited for providing primary control power. Furthermore, they are able to: ▪ Supply back-up power ▪ Peak Shaving ▪ Black start power plants ▪ Even out fluctuating generation ▪ Control grid voltage They can be directly integrated into the power plant process to provide primary and secondary control energy.
Investment	up to 1,500 Euro/kW
Timeline	Depending on the size – 6 to 12 months
Best practice (large scale)	Integrated (into a power plant) battery storage systems: ▪ Power plant battery Heilbronn – a joint venture between Bosch AG and EnBW; energy storage at hard-coal fired unit 7 consisting of 2 x containers of 2.8 MWh lithium-ion batteries, 6 x 900 kW inverters, 6 x 1000 kVA transformers and supplementary systems; erection started in November 2017, commissioning planned in spring 2018 Independent battery storage systems: ▪ STEAG Large Scale Battery System (Internet), PowerTech Journal 1,2/2017 and PowerTech Journal 4/2017 90 MW in total at six sites in Germany (6 x 15 MW), in operation since 12/2016 – investment of 100 million Euro ▪ Enercon; Feldheim (10 MW) 3,360 lithium-ion storage modules which are housed inside the 17 x 30 m storage building, in operation since 09/2015 – investment of 12.8 million Euro

Thermal storage

The most common thermal storage system is the hot water tank based on the sensible heat of water. A heating device produces hot water outside or inside an insulated tank where it is stored for a short period of time (a couple of days maximum). The stored energy depends on the hot water temperature and on the tank volume. The tank insulation determines the thermal loss and limits the storage period.
REF__4: www.ease-storage.eu/energy-storage/technologies/

In power plant applications excess heat is stored in low demand situations. It decouples the heat and power production and thereby increases power plant flexibility. The heat production capability is enhanced and forced power production is decreased. Subsequently, heat storage systems help to meet heat supply obligations. Therefore, this technology is especially suited for “Combined Heat and Power (CHP)”plants. The fields of applications and best

STEAM – THERMAL STORAGE	
Flexibility impact	Minimum load reduction, dynamic behavior
Limitations	Low demand / heat supply obligations
Description	▪ Incorporation of external thermal storage tank – mainly hot water tanks ▪ Various technologies for storage applicable (pressurized and unpressurized) ▪ Various operation concepts (load shifting, provision of extraction steam) applicable
Investment	300 – 500 Euro/m³ (unpressurized storage) 800 – 1,200 Euro/m³ (pressurized storage)
Timeline	Depending on the size – 6 to 12 months
Best practices or references	▪ FLEXI-TES joint research project, 2017 – 2020 ▪ I-TESS Study by Solar Institut Jülich ▪ GKM Mannheim

GKM uses an unpressurized flat bottom tank – Hedbäck design – with the following characteristics:

- Simple design
- Tank diameter: 40 m
- Cylindric tank height: 36 m
- Medium: water / steam
- Max. temperature: 98 °C
- Capacity: 43,000 m^3
- Heat storage capacity: 1,500 MWh
- Max. flow from/to the tank: 6,200 t/h

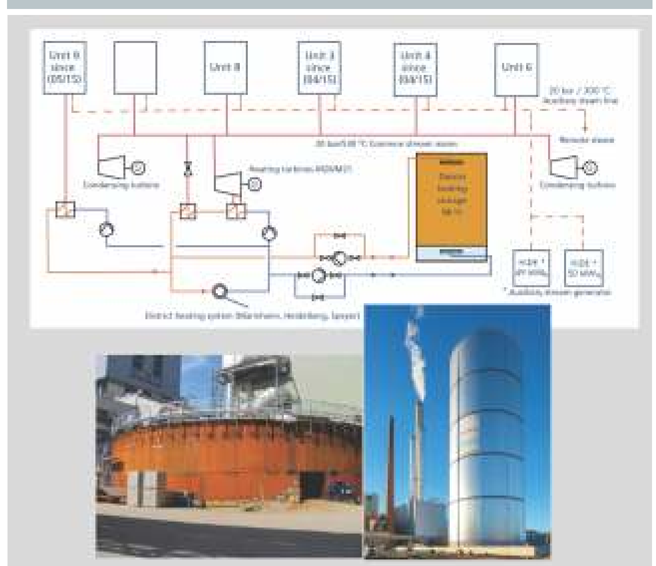
The GKM example is shown in the following figure.

Electric boilers

Another technical solution for decoupling heat and power production and enhancing operational flexibility is implementing electric boilers in a plant. This application is dedicated to CHP plants. The investment costs for this solution is in the range of 60 to 80 USD kW.

Source: Electric Power Planning & Engineering Institute (EPPEI) of China

Figure10 Thermal storage at the GKM power plant in Mannheim/Germany



Source: GKM

4. Flexibility in operation & maintenance

Flexible operation has an impact on plant operation and maintenance. In order to handle flexible operation, it is very important to closely monitor the operating data of critical components and equipment. This is essential for managing the consequences of flexible and/or cycling operation. In this context, the I&C system plays a crucial role and is discussed in this chapter.
Furthermore, this chapter includes practical tips for plant operation (covering different areas of the plant) as well as references dealing with the implications of flexible operation on lifetime, efficiency and costs.

4.1 Role of I&C

The I&C system is the key enabler of flexible operation. There are different levels of automation that can be found in existing power plants (see also Figure 11).

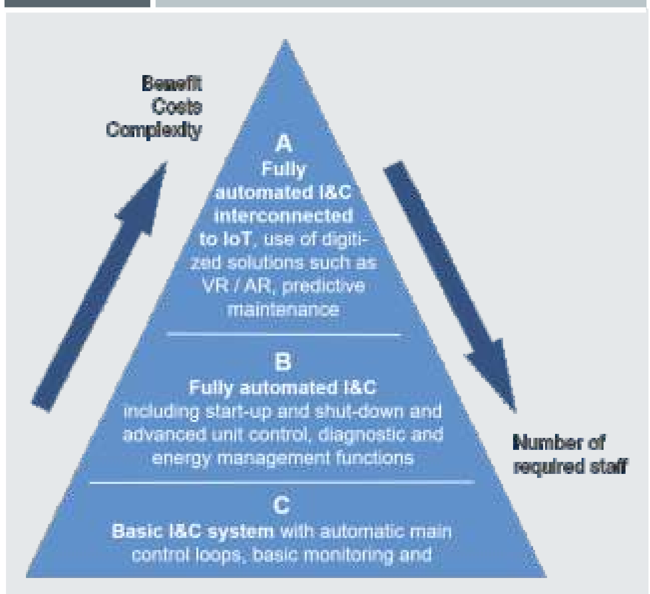
- **(C)** Basic I&C system: This represents the basic level required to operate the plant. It includes all measuring and protective functions as well as the basic monitoring and control of all processes.
- **(B)** Fully automated I&C: This comprises automated start-up and shut-down as well as advanced unit control concepts and diagnostic and energy management functions. It includes condition monitoring systems and lifetime consumption monitoring.
- **(A)** Fully automated I&C interconnected to the Internet of Things (IoT): The power plant, including all processes and procedures, are integrated in a digitized environment. This implies the use of innovative technologies such as Virtual Reality (to plan outages, to simulate plant behavior) or Augmented Reality (to support maintenance work) as well as big data solutions to tap the potential of predictive maintenance. Moreover, the plant is linked to the company-wide network.

Level (B) and (A) best facilitate flexible operation. In addition to automated operation, they provide the necessary tools for assessing the status of the plant.

I&C optimization is the most cost-effectiveway to enhance power plant flexibility

All existing control loops must operate smoothly before any optimization measure for enhancing flexibility is considered. In a next step, optimization potential should be identified and corresponding solutions should be implemented. The optimization of the I&C system is the most cost-effective way to enhance power plant flexibility. Relevant measures are included in chapter 3.4.

Figure 11 Different levels of an I & C system



4.2 Critical components

Introducing cycling operation to a coal-fired power plant engineered for predominant base load operation has an adverse effect on plant equipment. The life expectancy of the effected equipment is inadvertently reduced and there is an increase in the unplanned non-availability of the plant (see also Attachment A). The main problems introduced by the cycling

operation include pressure and temperature related stresses on components (creep-fatigue damage), wear and tear due to higher utilization and corrosion due to both changes in plant chemistry and water excess from increased condensation.
The following table lists the typical plant equipment most affected by cycling operation.

Table 4 List of critical components

PLANT EQUIPMENT WITH MOST SIGNIFICANT IMPACTS	PRIMARY DAMAGE MECHANISM
Boiler water-walls	Fatigue corrosion, corrosion due to oxygen and chemical deposits (depending on water quality)
Boiler super-heaters	High temperature differential and hot spots from low steam flows during start-up, long-term overheating failures
Boiler re-heaters	High temperature differential and hot spots from low steam flows during start-up, long-term overheating failures, tube exfoliation damages IP turbines
Boiler economizer	Temperature transient during start-ups
Boiler headers	Fatigue due to temperature ranges and rates, thermal differentials tube to headers; cracking in dissimilar metal welds, headers and valves
Drum	Thermo-mechanical stress at drum walls
LP turbine	Blade erosion
Turbine shell and rotor clearances	Non-uniform temperatures result in rotor bow and loss of desired clearance and possible rotor rubs with resulting steam seal damages
Feedwater heaters	High ramp rates during starts; not designed for rapid thermal changes
Air heaters	Cold end basket corrosion when at low loads and start up, acid and water dew point Enamel coating required at the cold end to avoid ammonium sulfate corrosion in case of SCR installation
Fuel system / pulverizers	Cycling of the mills occurs from even load following operation as iron wear rates increase from low coal flow during turn down to minimum
Generator	Thermo-mechanical stress on generator components especially at windings and insulation
Water chemistry / Water treatment	Cycling results in peak demands on condensate supply and Oxygen controls

These components need careful monitoring and frequent checks. It is highly recommended that industry guidelines such as the VGB-Standard S-506-R-00;2012-03.EN “Condition Monitoring and Inspection of Components of Steam Boiler Plants, Pressure Vessel Installations and High-Pressure Water and Steam Pipes”be complied with. The next table shows an overview of existing regulations and VGB standards with respect to condition monitoring.

Table 5 Existing regulations and VGB standards with respect to condition monitoring;

	PIPELINE	HEADER / DRUM	INJECTION COOLER
Calculation/ design	▪ VGB-R109 ▪ VGB-R507 section 4.3.2 with references to: FDBR Guideline “Design of power piping” and VDI manual Energy Technologies ▪ VGB-R501 (boiler interior) ▪ VGB-R503 ▪ VGB-R510 ▪ EN 13480-3 ▪ TRD series 300*, 508* ▪ AD 2000 series B/S ▪ AD 2000 series HP 100R (replacement for TRR 100) ▪ (TRR 100*) ▪ Finite elements method	▪ VGB-R109 ▪ VGB-R501 ▪ EN 12952-3 ▪ EN 13445-3 (A1 item 19) ▪ TRD series 300*, 508* ▪ AD 2000 series B/S ▪ Finite elements method	▪ VGB-R109 ▪ VGB-R501 ▪ VGB-R540 ▪ EN 13480-3 ▪ EN 13445-3 ▪ TRD series 300*, 508* ▪ AD 2000 series B/S ▪ Finite elements method
Extended inspection	▪ VGB-R508 ▪ VGB-R510 ▪ EN 13480-5	▪ VGB-R501 ▪ DIN EN 13445-5 ▪ DIN EN 12952-6	▪ VGB-R540 ▪ DIN EN 12952-6
Diagnostic test	▪ VGB-R509 (periodic inspection) in conjunction with VGB-R510 ▪ VGB-TW507 ▪ (microstructure rating charts)	▪ TRD series 500* ▪ VGB-R509 (periodic inspection) in conjunction with VGB-R510 ▪ VGB-TW507 ▪ (microstructure rating charts)	▪ TRD series 500* ▪ VGB-R540 in conjunction with VGB-R509 ▪ VGB-TW507 ▪ (microstructure rating charts)

Diagnostic lifetime calculation	▪ TRD 508* /EN 12952-4 ▪ TRD series 300* / EN 12952-3 ▪ Force/displacement transducer with diagnostic system by the manufacture ▪ Finite elements method	▪ TRD 508* / EN 12952-4 ▪ TRD series 300* / EN 12952-3 ▪ DIN EN 13445-3 A1 (Appendix M) ▪ Finite elements method	▪ TRD 508* /EN 12952-4 ▪ TRD series 300* ▪ EN 12952-3 ▪ Finite elements method

*) Regulations will not be updated anymore

4.3 Practical tips

The following table includes best practices and recommendations for flexible plant operation. It refers to the different plant areas and addresses issues that are important in cycling operation mode.

PLANT AREA	ISSUE / SPECIAL FOCUS	MITIGATION
Combustion		
Mills	▪ Minimum number of mills / burners / burner level ensuring a sufficient ignition and respectively combustion ▪ Minimum coal flow ▪ Air distribution control ▪ Inertia and smooth switch over	▪ Optimized combustion control based on the test run experiences in part load operation; special focus on reaction time and mill switch over; note: It is better running fewer mills at higher load than more mills at low load – the combustion stability increases. ▪ Optimized grinding: enables better usage of the fuel – improving the combustion process, precondition is the use of washed coal, respectively coal without stones, rocks and other hard impurities ▪ The control criterion for taking the first mill into operation should be the temperature inside the respective coal mill (classifier). This temperature should be higher than 70°C in order to avoid water dew point in the mill and, consequently, to avoid corrosions and blockings inside the coal mill caused by wet coal dust

PLANT AREA	ISSUE / SPECIAL FOCUS	MITIGATION
Burner	▪ Flame stability (flame pulsation and blow-off) ▪ Air distribution	▪ Reliable flame detection ▪ Improve air-fuel ratio ▪ Increase mixture and swirl ▪ Ensure equal coal dust distribution to burners ▪ Reduce cooling air flows ▪ Improve positioning accuracy of air control flaps ▪ To keep required steam temperatures at low load, use the upper burner levels in order to shift heat transfer from the evaporator to the superheater / reheater sections
Boiler general		Ensure proper purging
WATER-STEAM CYCLE		
Water chemistry	▪ Proper water and steam quality at all load conditions in order to avoid corrosion ▪ Cycling results in peak demands on condensate supply and oxygen controls	Strictly adhere to proven quality standards such as VGB-S-010-T-00; 2011-12.EN "Feed Water, Boiler Water and Steam Quality for Power Plants/Industrial Plants" – see Attachment B
Evaporator	▪ Differences of and material stress ▪ Avoidance of overheating	▪ Ensuring sufficient water / steam flow ▪ Optimize operation procedures or methods to reduce the ramp rate to the required or necessary minimum ▪ Check for design buffer in minimum feed water flow, especially in once through boilers ▪ Use circulation mode ▪ Monitor conditions

PLANT AREA	ISSUE / SPECIAL FOCUS	MITIGATION
Super-heater	▪ Differences of wall temperatures and material stress ▪ Temperature spread at life steam discharge	▪ Ensure sufficient steam flow ▪ Monitor conditions
Drum	▪ Minimum level ▪ Differences of wall temperatures and material stress ▪ Inertia during start-up	▪ Adhere to allowable temperature differences
Once-through circuit	▪ Switching point – from once-through to circulation mode	▪ Optimize mode change procedure between once-through and circulation operation
Feed water pump	▪ Minimum flow control ▪ Switch over (if more than one pump)	▪ Optimize part-load operation regime
TURBINE		
General	▪ Introduction of heating blankets	▪ Keep the turbine warm during stand-stills
HP and LP turbine	▪ Ventilation (reverse steam flow in the exhaust steam zone) ▪ Vibration excitation at the last-stage blades ▪ Water droplet erosion	▪ Implement protective functions in the HP and LP turbine ▪ Extend vibration monitoring ▪ Cool blades and casing (LP a, controlled flow and fast evacuation via direct link to condenser ▪ Improve condenser vacuum ▪ Optimize drainage
Chasing, bearings and shaft	▪ Vibration and expansion due to thermal stress	▪ Optimized start-up procedures ▪ EOH (Equivalent Operating Hours) counter to quantify the lifetime consumption due to thermal stress ▪ Improved condition and temperature monitoring

Table 6 Practical O&M tips

PLANT AREA	ISSUE / SPECIAL FOCUS	MITIGATION
Others		
Generator	Thermo-mechanical stress on generator components especially at stator windings	Integrate online monitoring and diagnosis: control of the cooling temperature, partial discharge measurement and stator end winding vibration measurements
DeNOx	▪ NH_3 slip ▪ Fouling and corrosion ▪ Ammonium sulfate formation	▪ Ensure minimum flue gas temperature at all load conditions (use higher burner level and higher air ratio) ▪ Improve dosing control ▪ Enamel coating required at the cold end
Flue gas desulfurization	▪ Reduction efficiency	▪ Ensure proper mass transfer – proper absorbent flow (increase liquid-gas ratio) ▪ Improved pump operation scheme

Need for preservation or lay-up procedures

Preservation or lay-up procedures are another important aspect. Boiler tube failures and other corrosion fatigue effects can be reduced by defining lay-up procedures, depending on the duration of the plant being off-line. For implementing suitable preservation procedures to protect equipment, the VGB Standard "Preservation of Power Plants" and "Preservation of Steam Turbo-Generator Set" could serve as a guideline – see Attachment C and D.

4.4 Impact on heat rate, lifetime consumption and costs

Heat rate

In principle two aspects have to be considered when analyzing the effect of cycling operation on a power plant's heat rate. On the one hand, cycling operation can lead to accelerated aging and thus to a permanent increase of the heat rate, which can be attenuated by appropriate maintenance and retrofit measures. On the other hand, operation in part load implicates a higher heat rate. The extent of this is limited to part load and does not lead to a change in the heat rate for base load operation.

- **Heat rate changes at cycling operation**

  The first effect, a general change of the heat rate by cycling operation, is difficult to quantify. Apart from the consequences of creep-fatigue on the power plant due to cycling, studies have also analyzed the negative effects on the heat rate (e.g. by the National Renewable Energy Laboratory – NREL – REF_1, REF_2). The heat rate of a power generating unit may typically degrade as much as 10 percent over a 30-year period even with routine maintenance and retrofit measures in place. One to five percent might be attributed to cycling (REF_1). The overall degradation of the heat rate given in these studies is comparable to experiences made in Germany.

- **Heat rate changes at part load operation**

  The second effect, the dependency of the heat rate on the part load operation, is slightly easier to estimate. A first indication can be gained from heat balance diagrams. Since boiler efficiency usually does not change much or rather improves slightly in moderate part load, the increase in the heat rate is mainly caused by a decrease in efficiency of the water-steam cycle and non-proportional decrease of auxiliary power. If the load is further decreased, for example to one-mill operation mode, the efficiency cannot be considered as the leading parameter. The higher-ranking aim for this operation is then to keep the unit in operation and avoid costs caused by another start-up. A clear increase in the heat rate is unavoidable.

Lowering the minimum load has an impact on the plant efficiency and on the specific CO_2 emissions respectively. However, the savings in CO_2 emissions arising from a higher share of renewables outweigh the effect of lower part load efficiencies of thermal plants. Nevertheless, measures to improve the heat rate in part load operation have to be worked out for every power plant individually.

References:

REF_4.1 – Power Plant Cycling Costs, N. Kumar et al., NREL, 2012

REF_4.2 – Flexible Coal, Jaquelin Cochran et al, NREL, 2013

Lifetime consumption

Flexible operation – especially cold start-ups and load changes of more than 50 percent of the nominal load – imply a high level of thermal stress, in particular to thick-walled components. The lifetime consumption of a particular component is influenced by many factors and is very specific. Therefore, it is very important to monitor the condition of these parts and to assess the lifetime consumption using lifetime monitoring systems.

These systems are designed for the continuous monitoring of stress on thick-walled components of power plant boilers and turbines, based on the procedure defined in official standards such as TRD code and DIN EN 12952. They provide information for each monitored component with respect to total fatigue – creep and fatigue– and use the temperature difference of the thick-walled components, which is either measured or calculated based on an appropriate model. Frequent inspections with physical checks – using X-ray examination, crack testing and microstructure examination – should be executed to verify the results of the lifetime monitoring systems. Lifetime consumption cannot be directly linked to a certain cost impact. The potential loss in revenue due to failed equipment depends on the business model and on the future operating regime as well as maintenance and repair strategies.

Reference:

REF_3 – Flexibility of thermal power plants, Agora Energiewende, 2017

Costs

It is not possible to make an overall statement for O&M costs as they strongly depend on the future load profile. There should be a market design that provides incentives to invest in flexible enhancement measures. Even with lower PLFs a commercial viable operation of the plant should be possible. In addition to the power supply, suitable ancillary services such as the provision of frequency and voltage control as well as black start ability could be considered as reimbursable deliverables.

Estimating the cost impact on an individual power plant in a cycling mode is not a trivial process. Each plant has undergone numerous physical modifications over the years and is unique in a number of ways. To provide an exact evaluation of the cost impact resulting from cycling operation, an in-depth analysis of each plant is necessary. Therefore, cost indications in this chapter and all following chapters should be interpreted as a guideline only, albeit one based on studies of similar plants.

The cost impact associated with the introduction of cycling operation can be categorized as follows:

1. **Hot, warm, and cold-start costs:**
   Apart from fuel and other auxiliary costs, cycling results in further operation, maintenance and capital (overhaul expenditures) costs. These do not include routine, fixed O&M costs

2. **Forced Outage Rates (EFOR) as a function of start type:**
   EFOR costs depend directly on the market and contractual agreements under which the plant is operating. It may include lost revenue and an obligation to procure replacement capacity on the spot market

3. Load following costs (significant load follows):

These costs incur due to increased damage to equipment due to significant (15 to 20 percent of maximum continuous capacity) load following

4. Start-up costs – fuel and auxiliary power + chemicals + water:

The costs of start-up fuel, auxiliary power, etc. forms a significant part of the total costs of cycling

5. Heat rate effects due to power plant cycling:

Studies have shown that a loss in efficiency over a certain time period might be attributable to cycling. Additionally, reduced efficiency in part load operation also causes an increase in fuel consumption

Decisions taken on preparing and modifying a plant for increased cycling operation strongly depend on business case justifications, which are extremely specific to market and context.

5. TRAINING CONCEPTS AND SKILLS PROGRAMS

To implement flexible operation regimes, it is essential to prepare a plant's personnel for this new situation. Whereas the ultimate goal in the past was to operate a plant in base load at highest efficiencies, this has changed completely in this time of energy transition. Therefore, it is strongly recommended to setup a suitable training program for power plant staff aiming at achieving:

- In-depth technical understanding for flexible operation and its consequences for O&M
- Understanding of the requirement and need for flexibility and change of operating paradigm and
- Changed mindset and motivation to tackle new challenges.

The **Kraftwerksschule e.V.** (KWS – PowerTech Training Center) compiled the report “Required Training for Flexible Operation of Coal-Fired Power Plants in India” with support from the Indo-German Energy Forum. The explanations included in this chapter are based on this report. They provide guidance and suggestions on how to develop and implement individual training programs.

The KWS concept addresses the training needs of the following groups of power plant personnel:

- **Management**
  - Senior engineer
  - Trainer
- **Operational staff**
  - Supervisor
  - Operator
- **Maintenance staff**
  - Mechanical
  - Electrical
- **Coordinators**
  - Operation
  - Grid

The recommended training plan comprises modules in preparation, flexibility, simulator, and competency, with a wide range of technical topics for both design types of coal-fired power plants. During the training phase, the performance and progress of each trainee should be thoroughly assessed and verified. Specific training enables participants to actively and purposefully apply the knowledge and skills they have acquired in theory and practice in their new field of activity. Graduation exams with participation certificates and exams with graduation certificates document training success and assist power industry businesses with HR development.

A complementary learning tool of choice is the power plant and grid simulator. The training simulators should be based on the technical data of real power plants and the grid. Modularized simulator training may benefit a wide range of target groups, such as operating personnel (power plant operators, foremen, grid operators), operational management personnel (shift supervisors, team leaders, unit leaders, master craftsmen), and technical personnel (technicians, chemists).

5.1 Training needs for different power plant personnel groups

Management personnel

Senior management are recommended to have specialized training in business management and in handling the technical and operational limitations of flexible production caused by participating in the flexibility program (ancillary grid services). In addition, emergency management rehearsals for black-out conditions, black start and grid restoration procedures are also recommended.

The following table provides an overview of the training program for management personnel.

Table 7 Flexibility training program for management personnel

TYPES	CLASSROOM WORKSHOP	SIMULATOR WORKSHOPS
Characteristics	▪ Business methods for handling technical and operational limitations for the participation of the “Home Plant” in the Flexibility program ▪ Deep and wide understanding of economic context with close relation to the requirements of the flexible market ▪ Operational and organizational strategies for customized plant structures: shift schedules, shift systems (4, 5, 6 shift systems), minimum number of control room staff, plant operation management for the production and maintenance, spare part management, workshop organization, etc. ▪ Broad understanding of grid requirements and load dispatcher tasks ▪ Hazards of plant and grid outages, black start-up procedures, auxiliary systems for black start-up capabilities, grid rebuild procedures after outages	**Power plant simulator** ▪ Operation procedures for quick start-up, shut-down, load ramps, limitation of minimum load ▪ Management of fuel consumption and technical resources during times when the market price for electrical power is high ▪ Methodologies for mitigating the effects of malfunctions ▪ Plant efficiency during minimum load conditions and load ramps ▪ Risk management during plant operation **Grid simulator** ▪ Grid behavior under different load conditions (voltage, frequency, inductive and reactive power behavior) ▪ Properties of dense city grids or long span transportation lines ▪ Communication with local utility companies, load dispatchers or other plants ▪ Grid rebuilt and set up procedures ▪ Emergency management during outage conditions of grid and/or plant
Achievement	Certificate of attendance	Certificate of attendance
Potential function	Promotion to a function on company level (senior manager, senior advisor)	Promotion to a function on company level (senior manager for ancillary services, senior advisor for flexible operations on fleet level)

Operating personnel

The flexibility training program's key target group are control room personnel. As already stated in chapter , the I&C system is the heart of flexibility. Therefore, operating personnel need to be trained and skilled to use these technologies and to draw the right conclusions when analyzing the monitoring and assessment systems. The following table provides an overview of the training program for operating personnel.

Table 8 Flexibility training program for operating personnel

TYPES	PREPARATION OPERATION TRAINING	FLEXIBILITY OPERATION TRAINING	SIMULATOR TRAINING
Characteri-stics	▪ Refreshment training ▪ Preparation for participating in the Flexibility Training ▪ Plant generic but specific technical content ▪ Design and operation of the "Home Plant" ▪ Basic understanding of economic context with close relation to plant requirements	▪ Preparation for participation in the Simulator Training ▪ Broad technical understanding comprising various plant technologies ▪ Enhanced knowledge of technical limits and options to cope with those limitations during flexible operation ▪ Understanding economic context with close relation to plant requirements ▪ Basic knowledge of operating and maintenance procedures ▪ Optional: Classroom trainer for the flexibility project (shift supervisor status or Engineer certificate required) trainer (Train-the-trainer training)	▪ In-depth knowledge of operating and maintenance procedures ▪ Development of new operation procedures ▪ Broad understanding comprising the complete scale of plant operation ▪ Professional handling of malfunctions ▪ Professional handling of high speed start-up and shut down procedures and loads ramps ▪ Optimization of cold, warm and hot start- up procedures ▪ Handling of outage conditions ▪ Black start-up procedures ▪ Decision and control room staff management ▪ Leadership training ▪ Cultural change of operation competencies, gaining operative excellence ▪ Learning to take proactive approaches operating the plant ▪ Regular virtual plant checks

			▪ Optional: Simulator trainer (Train-the-trainer for simulator training)
Target group	Operating personnel (local and control room)	Control room personnel, shift supervisors and shift engineers	Control room shift groups
Achievem-ent	Qualified Prep-op-certificate (compulsory for the Flexibility Training modules) (optional: recommendation for further promotion)	Qualified Flex-op-certificate (compulsory for the Simulator Training modules) (optional: recommendation for further promotion)	Sim-Flex-certificate (optional: recommendation for further promotion)
Certificate	Oral and written tests	Oral and written tests	Practical test of plant operation employing the simulator Practical test of shift group management during flexible operation as shift supervisor
Potential function	Local and control room operators	Control room operators, foremen or shift supervisors	Shift supervisors, flexibility advisors for shift supervisors, operation and grid coordinators or simulator trainers

Technical personnel

It is necessary for this group to learn about the technical solutions required to expand the plant's load and operating range. This roup of staff also should be able to develop even more advanced solutions for problems like unsatisfactory load gradients, minimum load conditions, wear or fouling problems. The technical staff group should be divided into two subgroups:

- Mechanical maintenance staff
- Electrical and automation staff

Depending on the content of the training modules, joint training sessions are advisable and helpful. The following table provides an overview of the training program for technical

Table 9 Flexibility training program for operating personnel

TYPES	**PREPARATION TECHNICAL** TRAINING	**FLEXIBILITY TECHNICAL** TRAINING
Characteristics	▪ Refreshment of know how ▪ Preparation for participation in the Flexibility Training ▪ Plant generic but specific technical contents ▪ Design and operation of the “Home Plant” concerning service and maintenance procedures ▪ Basic understanding of economic context with close relation to maintenance requirements	▪ Broad technical understanding comprising various plant technologies ▪ Enhanced knowledge of maintenance methods and strategies to cope with maintenance requirements during flexible operation ▪ Enhanced understanding of economic context with close relation to plant and maintenance requirements ▪ Basic knowledge of operating procedures ▪ Broad understanding of economic context with close relation to maintenance requirements ▪ Optional: Classroom trainer for the flexibility project (maintenance supervisor status or Engineer certificate required)
Target group	Mechanical, electrical and automation maintenance or service staff (local and workshop)	Mechanical, electrical and automation maintenance or service staff (local, workshop and management)
Achievement	Qualified Prep-tech-certificate (compulsory for the Flexibility Training modules) (optional: recommendation for further promotion)	Qualified Flex-tech-certificate (optional: recommendation for further promotion)
Certificate	Oral and written tests	Oral and written tests
Potential function	Local and workshop service staff	Service foreman, maintenance supervisor, maintenance coordinator

5.2 Train the trainer

To sustain the training efforts, train the trainer sessions should be a key focus. KWS has developed a specific training module that aims to systematically prepare staff to become lecturers and trainers. At first, participants are familiarized with the requirements of the coach's role and then deal with the basics of learning. Participants learn how to plan and implement lessons, and how to select and prepare content to suit their objectives and target groups. Based on this, moderation techniques and criteria for the selection and use of adequately supported media are developed in order to transport learning content effectively.

An additional focus is the control of group dynamics. Participants learn to work with groups, guide them and motivate them to solve conflicts in the classroom and to deal appropriately with interferers.

Furthermore, participants deal with strategies analyzing the training needs of individuals and teams in organizations. Finally, participants also learn about quality assurance techniques and methods, and learn about the opportunities of education control.

The module includes two deepening practical exercises in which, under the guidance of professional trainers and in exchange with other participants, the learning is deepened and expanded. Practical project work will also be conceived and presented during these practical exercises. The course content is intended for those who are already engaged in further education and training in companies and who wish to further qualify.

6. FLEXIBILITY AND MANAGEMENT

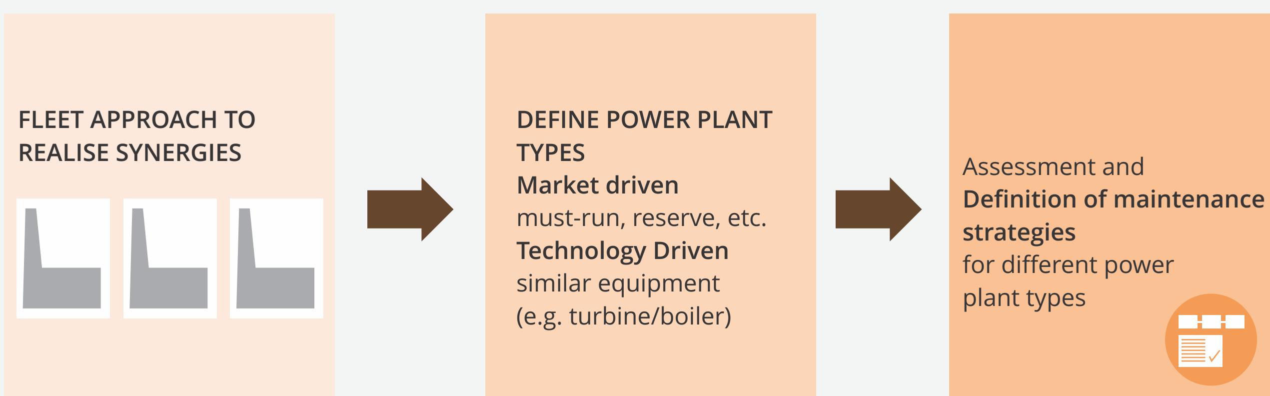
This chapter comprises aspects and tasks the power plant management should address in the transistion process toward flexible operation. There are different areas of activity such as:

- Implementation of new business models: Align plant operation with commercial strategies, e.g. provide ancillary services
- Change management: Raise awareness for the need for flexibilty and implement change processess
- Skill and talent management: Ensure the required level of technological expertise and motivation is gained as well as superordinate understanding (see training chapter)
- Quality awareness: Raise awareness for the importance of quality and adherance to O&M procedures
- Organization: Install new work flows, procedures and processes – especially for maintenance – that align with the new operation requirements (e.g. two-shifting, weekend shut downs)

6.1 Fleet approach

If a power plant company operates several plants it is recommended to consider a fleet approach.

Figure 12 Fleet approach



Overall fleet equipped with a uniform autoomation technology ensuring data transparency and advanced data assessment as well as benchmarking

The benefits of a fleet management approach are standardization, harmonized working and reporting procedures, and the exchange and sharing of experiences and lessons learned. This approach is not a new development. However, it should be reassessed considering the impact of flexible operation.
The first step to derive the right maintenance strategies is to classify the power plant according to market requirements. In Germany the following approach has been developed. The basic idea is to cluster power plants into three different categories:

- Must run plants: Need to fulfill a dedicated power purchase agreement and/or heat-supplycontract
- Market followers: Adjust their operating regime to the (merit-orderbased) market with a large share of cycling operation
- Reserve plants: Need to be available to satisfy power demand, if required

The following table provides an overview of the three plant categories.

Table 10 Market-driven fleet approach for maintenance; source: VGB and Uniper

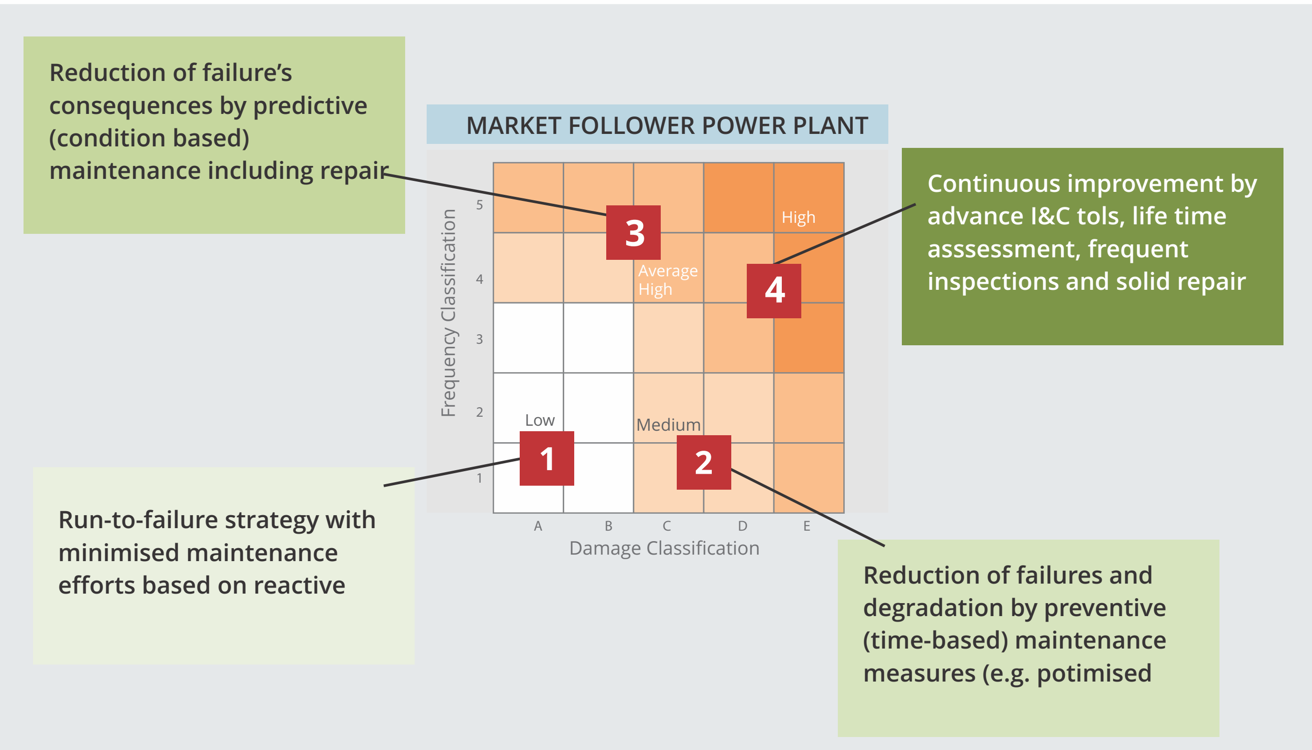
	MUST RUN (CONTRACTUAL)	MARKET FOLLOWER	RESERVE
Characteri-stics	Operation according to customers' needs for electricity and/or heat	Market prices rule plant operation	Operation on demand of the TSO (Transmission System Operator)
Availability	> 90 %	< 80 %	on demand
Utilization	70 to 80 %	35 to 50 %	1 to 5 %
Maintena-nce approach	▪ Preventive mainte-nance in wear-intensive areas (mills, boiler, FG-cleaning) ▪ Condition based maintenance ▪ Overhaul cycles and durations are time-dependent	▪ Risk-based maintenance ▪ Advanced condition monitoring ▪ Overhaul cycles are cost-optimized and based on equivalent operating hours ▪ Longer stand-stills	▪ Condition-based maintenance ▪ Frequent plant tests and start-ups to secure reliable operation if requested ▪ Long stand-stills ▪ Need for a concept to maintain know-how

The operational regime remains stable over the contractual period for must-run and reserve power plants. Market followers suffer from increased lifetime consumption. Clearly, the plant categories used in Germany will have to be adapted for other markets, including the Indian market. However, a systematic approach with suitable categories would be beneficial in India just as it is in Germany.

For a market follower, plant maintenance measures are selected based on a risk assessment. Increased risk goes hand-in-hand with increased inspection effort. The optimum needs to be found, based on an evaluation of reliability versus (maintenance) costs. The following figure shows the relation between maintenance approaches and risks. This implies that components or parts for power plants, which are very sensitive to cycling operation, need to be maintained and controlled very tightly (see also); e.g.:

- Thick-walled components: headers, valves, T-and Y-pieces, casings, turbine rotor
- High-temperature components: super-heater, re-heater
- Pipe hangers
- Turbine: ND-part
- ECO and air pre-heater
- Generator: winding and insulation

Figure 13 Risk-based selection of maintenance measures; source: VGB and EnBW



7. Specifics for India

The Indian government has set ambitious targets for renewable energies: Installed capacity should grow to 175 GW by 2020, of which 100 GW should come from solar, 60 GW from wind, 10 GW from hydro (>25 MW) and 5 GW from biomass. This requires a radical transformation of the energy system in India, as approximately 65 percent of existing installed capacity (334 GW) currently comes from thermal power generation. The following table shows an overview of the installed base in India as of December 2017.

Table 11 Overview of the installed capacity in India; in GW

Install. capa-city	Total	Renewables				Thermal				Nuclear
		Solar	Wind	Hydro*	Biomass	Gas	Diesel	Coal	Lignite	
India	333.6	17.1	32.9	49.4	8.5	25.1	0.8	193.0	-	6.8
		107.9				218.9				

*including all hydro

The increasing share of variable renewable energies will result in less operating hours as well as in flexible operation regimes of India's conventional – mainly coal-fired – power plants. The Indian coal – which is the key source for the majority of coal-fired power plants in India – has some special properties which also have an influence on the flexible operation. The ash content of Indian coal is significantly high – up to 50 percent. An overview of the composition of Indian coal in contrast to German lignite and imported hard-coal applied in German plants is shown in the next table.

Table 12 Overview of typical coal compositions

TYPE OF COAL	CALORIFIC VALUE [kJ/kg]	ASH CONTENT [%]	WATER CONTENT [%]	SULPHUR CONTENT [%]
Indian coal	11,715 – 20,900	25.0 – 50.0	10.0 – 20.0	0.30 – 0.80
German lignite	7,800 – 11,300	2.5 – 20.0	40.0 – 60.0	0.15 – 3.00
Imported hard coal Indonesia	~ 23,000	10.0 – 15.0	10.0 – 30.0	~ 1.0
Imported hard coal South Africa	~ 27,000	15.0 – 17.0	~ 8.0	< 1.0
Imported hard coal Colombia	25,000 – 34,000	3.0 – 10.0	3.0 – 12.0	~ 1.0

Almost half of the coal-fired units have a capacity of more than 500 MW. Approximately one third accounts to units with a size of less than 250 MW. Two third of the installed coal base was commenced after 2003. Furthermore, the Indian plants are faced with new, stricter emission requirements. These requirements will result in massive retrofits of existing plants with DeNOx and DeSOx technologies.

Low minimum load requires coal treatment

Taking the Indian situation into account, the following aspects should be reflected for a more flexible operation of Indian power plants:

1. The **standard design** and set-up of Indian coal-fired power plants **entails some favorable configurations** for flexible operation – e.g. they are equipped with a high number of mills, tilting burners and frequency-driven fans and actuators.
2. Due to the **coal quality** it is unlikely that Indian power plants are able to reduce the minimum load below 25 percent without any additional coal treatment. Therefore, a concept for homogenization and enhancing coal quality should be developed. Such a concept could include washing, blending, coal cleaning at site as well as online coal analysis.
3. The flexibility potential by means of **I&C adjustments** is significant because the level of automated and advanced controls leave room for improvements. Especially with respect to a fast and efficient start-up, manual interventions should be reduced to a minimum. In order to enhance the dynamic behaviour of the plant and to positively contribute minimum load and cycling operation, advanced unit control concepts such as condensate throttling and throttling of the extraction steam for the HP pre-heater are very beneficial. This modification helps fulfilling the requirement of providing 5 percent frequency control power.
4. In order to ensure proper combustion control and thereby guaranteeing a reliable minimum load operation, proper **flame detection**– individually for each burner – is essential. The current hardware installed in many Indian power plants needs to be considered for potential replacement.
5. Flexible operation with cycling, part load and minimum load operation should be considered in the **design of the flue gas equipment.** The flue gas treatment needs to comply with environmental norms at all potential load conditions. Cycling load operation has an impact on DeNOx and DeSOx systems – e.g. pumping operation scheme and dosing control.

Appendix A: VGB standard "Feed Water, Boiler Water and Steam Quality for Power Plants / Industrial Plants"

VGB-S-010-T-00;2011-12.EN, Table of contents

VGB-S-010-T-00;2011-12.EN VGB

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VGB
VGB-Standard
Feed Water, Boiler Water and Steam Quality for Power Plants / Industrial Plants

Appendix B: VGB standard "Condition Monitoring and Inspection of Components of Steam Boiler Plants, Pressure Vessel Installations and High-Pressure Water and Steam Pipes"

S-506-R-00;2012-03.EN; Table of contents

VGB VGB-S-506-R-00;2012-03.EN

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Appendix C: VGB standard “Preservation of Power Plants”

VGB-S-116-T-00-2016-04-EN

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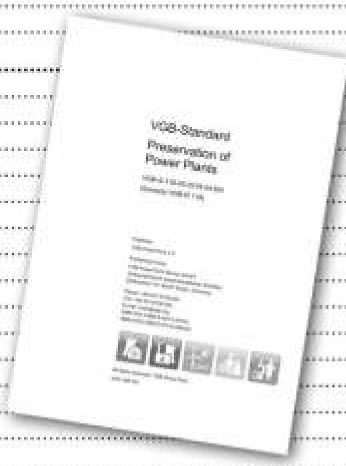
VGB-Standard
Preservation of
Power Plants

VGB-S-116-00-2016-04-EN



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VGB-Standard
Preservation of Power Plants

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Appendix D: VGB standard "Preservation of Steam Turbo-Generator Sets"

VGB-S-036-T-00-2014-08-EN

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Figures

Appendix E: Further Literature Recommendations

- **Flexibility in Thermal Power Plants - With a Focus on Existing Coal-Fired Power Plants**
  Study of Agora Energiewende, June 2017

The study provides a broad analysis on possible flexibility measures for thermal power generation, focussing on coal power plants: The first part of the study analyses major challenges related to the integration of large shares of renewable. The second part describes in detail current technical characteristics related to the flexibility of thermal power plants. The third part analyses some retrofit measures to increase the flexibility of coal power plants, including their technical and economic parameters. Fourth, our findings with regard to challenges and opportunities are discussed and put into perspective by spotlighting the situation in South Africa and Poland, two countries with large coal power generation shares.

Download here: https://www.agora-energiewende.de/en/publications/flexibility-in-thermal-power-plants-1/

- **Final Report of the Joint Project "Partner Steam Power Plant"**
  Report by VGB, 2015

The research project „Partner Steam Power Plant" will clearly improve the appropriate integration of power generation from fluctuating energy sources. Therefore, existing power plants shall handle fluctuations of power generation from wind or photovoltaic even better in order to guarantee the energy supply.

Download here: https://www.vgb.org/en/research_project375.html

- **Increasing the Flexibility of Coal-Fired Power Plants**
  IEA Report 242, Colin Henderson, September 2014

Coal-fired power plants are increasingly required to balance power grids by compensating for the variable electricity supply from renewable energy sources. For this, high flexibility is needed, in terms of possessing resilience to frequent start-ups, meeting major and rapid load changes, and providing frequency control duties. This report reviews the means available and under development for achieving the flexibility. Potential damage mechanisms are well known, and the necessary flexibility can be achieved with acceptable impacts on component life, efficiency and emissions. Designs are being developed to enable flexibility in future plants.

Download here: https://www.usea.org/sites/default/files/092014_Increasing%20the%20flexibility%20of%20coal-fired%20power%20plants_ccc242.pdf

- **Required Training for Flexible Operation of Coal Fired Power Plants in India**
  Report by KWS

With the rapid expansion of India´s renewable power plant capacities and the increasing complexity ofpower plant technology, the need for standardized and customized high-quality personnel training throughoutthe industry is evident. The necessity of training is based on clear recommendations described in thisreport.

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