International Renewable Energy Agency

FLEXIBILITY IN CONVENTIONAL POWER PLANTS

INNOVATION LANDSCAPE BRIEF

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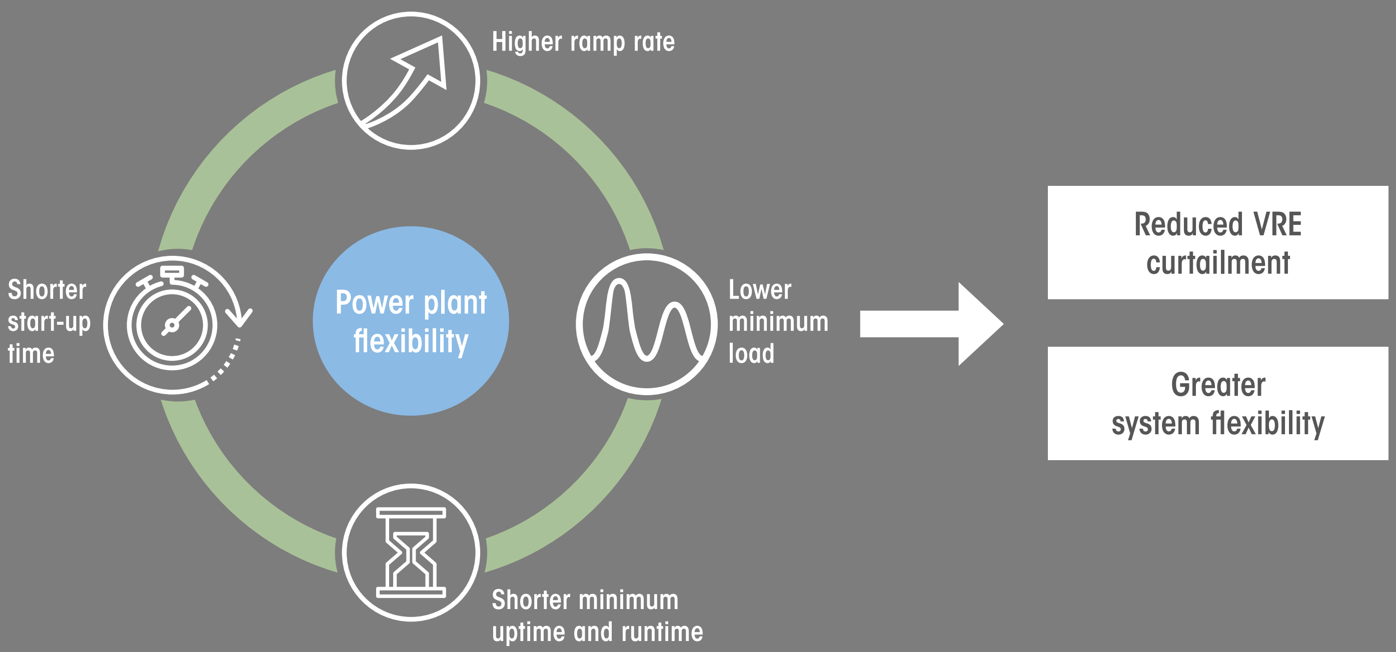
1 BENEFITS

Refurbishments can increase the flexibility of conventional power plants, enabling the integration of higher shares of variable renewable energy (VRE)



2 KEY ENABLING FACTORS

- Update market design to reward flexible operation
- Adapt contracts for fuel supply and capacity provision
- Update standards, grid codes and market rules

3 SNAPSHOT

- **China:** Flexible thermal plant operation resulted in a 30% reduction in VRE curtailment
- **India:** Reducing minimum generation levels for thermal plants from 70% to 55% has reduced VRE curtailment from 3.5% to 1.4%
- **Germany:** Refurbishment of a coal power plant reduced minimum load by 170 MW and increased ramp rate by 10 MW per minute

FLEXIBILITY IN CONVENTIONAL POWER PLANTS

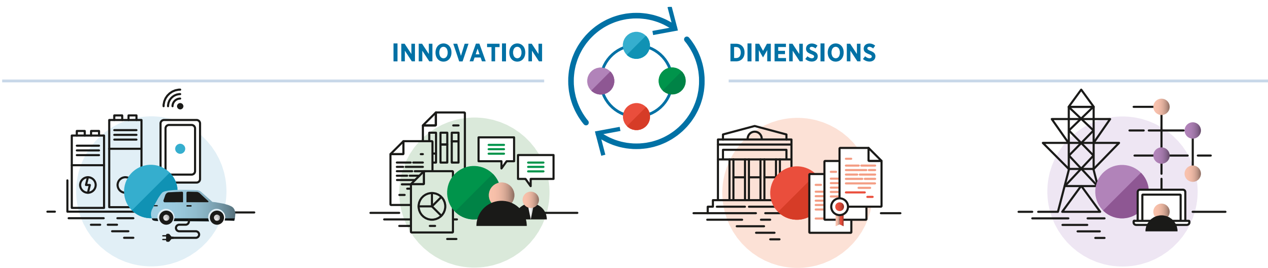
Existing conventional plants, operating alongside growing shares of renewable power generation, can be refurbished to provide **supply-side flexibility.** This helps to accommodate **solar PV and wind generation variability** in the short to medium term.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

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4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
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11 Flexibility in conventional power plants

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26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
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Improving the flexibility of thermal power sources, as a short- to medium-term solution, is an important component of the energy system transformation with an increasing share of renewable energy. It supplements other flexibility solutions such as energy storage, demand-side management and increased interconnection. For the foreseeable future in many regional contexts, existing conventional power plants will operate alongside renewable energy plants and will play an essential role in accommodating increasing supply-side variability. This brief examines how less flexible generation technologies can be improved through retrofits to support VRE integration, unlocking flexibility from existing infrastructure.

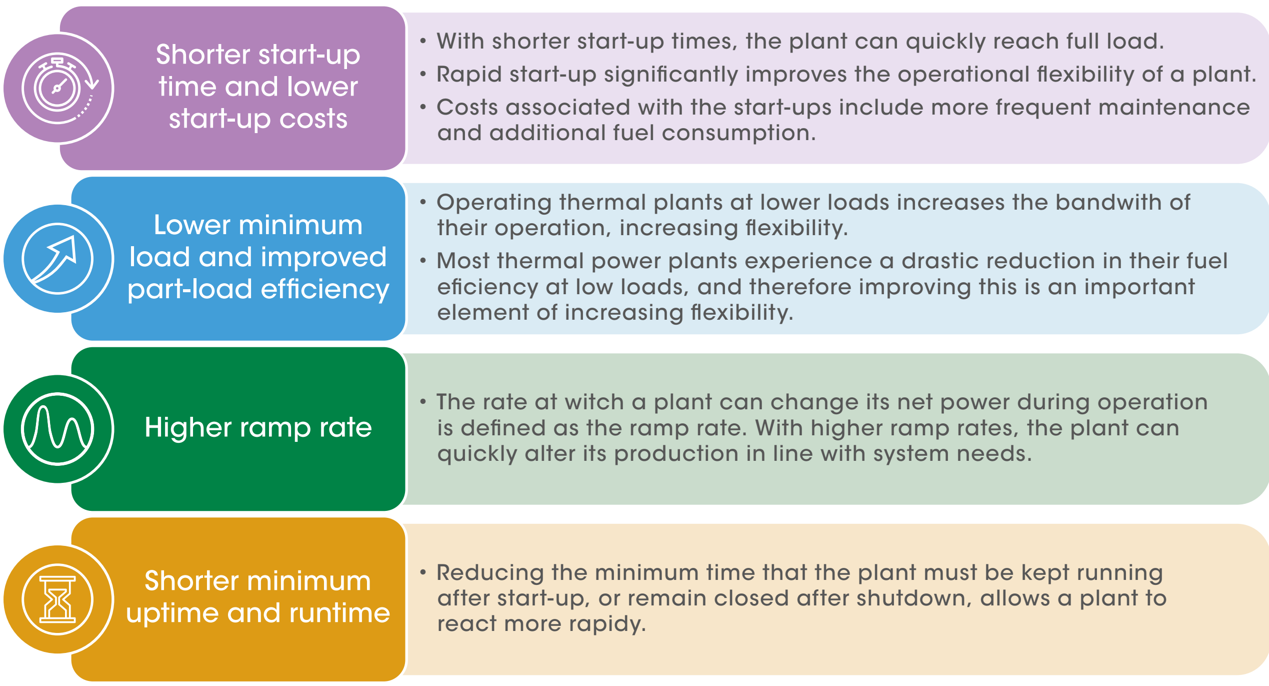
The brief is structured as follows:

I. DESCRIPTION

Dealing with variability and uncertainty in balancing the power system is not a new issue for power system operation. Demand has always been variable to some extent and generation has typically been adjusted to meet the demand in real time. Integrating a higher share of VRE in the system increases variability, which in turn increases the need for more flexible generators in the system.[1]

While most conventional plants have limited flexibility, emerging technological innovations and retrofits can enhance their ability to better respond to variability in renewable energy generation. Increasing the flexibility of conventional power plants involves retrofitting certain physical components, as well as making operational modifications to achieve the objectives shown in Figure 1.

Figure 1: Objectives of flexibilization



Adapted from: Vella (2017), Agora Energiewende (2017).

1 Flexible operation of thermal plants refers to their capability to cope with the variability and uncertainty that solar and wind generation introduce at different time scales, avoiding curtailment of power from these VRE sources and reliably supplying all customer energy demand (IRENA, 2018). This brief addresses short-term flexible operation, from seconds to hours.

Conventional power sources range from baseload power plants, characterised by lower flexibility, to peaking power plants, characterised by relatively high levels of flexibility. For example, nuclear power plants are by definition inflexible, followed by coal and then gas power plants, which typically cover the area between baseload and peak load, so-called "intermediate load". Natural gas-fired baseload power plants, *e.g.* combined-cycle gas turbines (CCGT), are less flexible in operation than open-cycle gas turbine (OCGT) power plants,[2] which can also cover peak load. Natural gas-fired internal combustion engine (ICE) power plants are typically used for applications requiring high levels of operational flexibility. Oil-fired ICE plants (diesel/fuel oil) provide even greater flexibility in some applications, but they come with the highest operational costs.

Refurbishments to increase flexibility sometimes address the need to operate the plant frequently at low loads. This will reduce the capacity factor of the plant,[3] which in turn increases the levelised cost of energy (LCOE), since the capital cost and fixed expenses are divided over fewer units of produced electricity. Furthermore, operating at low load factors reduces plant efficiency thereby increasing fuel costs per unit. Operating a plant flexibly may therefore increase operation and maintenance costs. From a system, instead of a generation plant owner, perspective these increases are, however, small compared to the fuel savings associated with higher shares of renewable generation in the system (Agora Energiewende, 2017).

Table 1 summarises the flexibility parameters of different technologies used in conventional power plants, before and after refurbishment to make the plant more flexible. Parameters can be improved to a certain extent depending on factors such as the age and design of the power plant. In power systems with low to medium levels of VRE penetration, enabling flexible operation of existing assets is one of the most efficient ways to ensure the integration of VRE in the system (Energinet, 2018).[4]

Table 1 Comparison of flexibility parameters before and after flexibilisation initiatives

Type of point		Start-up time*	Start-up cost (USD/MW instant start)	Minimum load [% P_{nom}]	Efficiency (at 100% load)	Efficiency (at 50% load)	Avg. ramp rate [% P_{nom}/min]	Minimum uptime	Minimum downtime
Hard coal	**Average plant**	2–10 h[a]	> 100	25–40%[a]	43%	40%	1.5–4%[a]	48 h	48 h
	Post flexibilisation	80 min–6 h[a]	> 100	10–20%[b]	43%	40%	3–6%[a]	8 h	8 h
Lignite	**Average plant**	4–10 h[a]	> 100	50–60%[a]	40%	35%	1–2%[a]	48 h	48 h
	Post flexibilisation	75 min–8 h[c]	> 100	10–40%[b]	40%	35%	2–6%[c]	8 h	8 h
CCGT	**Average plant**	1–4 h[a]	55	40–50%[a]	52-57%	47-51%	2–4%[a]	4 h	2 h
	Post flexibilisation initiatives	30 min–3 h[a]	55	20–40%[c]	52-57%	47-51%	8–11%[c]	4 h	2 h
OCGT	**Average plant**	5–11 min	< 1–70	40–50%	35–39%	27–32%	8–12%	10–30 min	30–60 min
	Post flexibilisation/ advanced plant	5–10 min	< 1–70	20–50%	35–39%	27–32%	8–15%	10–30 min	30–60 min
ICE [c]	**Average plant**	5 min	< 1	20% (per unit)	45–47%	45–47%	> 100%	< 1 min	5 min
	Post flexibilisation/ advanced plant	2 min	< 1	10% (per unit)	45–47%	45–47%	> 100%	< 1 min	5 min

* Start-up times are longer for cold start-up (plant shut for more than 48 hours) than for hot start-up (plant shut for less than 8 hours).

Notes: h = hour; min = minute; MW = megawatt; Pnom = nominal power.
Sources: [a]Agora Energiewende (2017); [b]Henderson (2014); [c]Feldmüller (2017); [d]Wärtsilä and Roam Consulting (2018).

2 CCGT power plants have a steam turbine in addition to a gas turbine. The waste gas from the gas turbine is routed to the steam turbine. In open-cycle power plants, waste gas from the gas turbine is not captured.

3 The capacity factor is the ratio of the total energy produced over a defined period to the energy that would have been produced if the plant had operated continuously at the maximum rating.

4 The report assumes that market incentives/price signals are a precondition.

Increased flexibility of coal power plants

In the case of coal-fired plants, increased flexibility can be achieved through process improvement, increased automation and retrofitting certain plant components. A list of the available options to achieve flexibilisation in coal-fired power plants is shown in Table 2.

Table 2 Options to increase flexibility in coal-fired power plants

Options	Flexibilisation objectives achieved	Description	Impact
Indirect firing	Lower minimum load	Indirect firing involves setting up a dust bunker between the coal mill and the burner to store pulverised coal. During periods of low load, auxiliary power can be used for coal milling, thereby reducing total power injected into the grid.	Indirect firing together with staged vortex burner retrofit can decrease the minimum stable firing rate from 25–30% to 10%.
Switching from two-mill to single-mill operation	Lower minimum load	Switching to a single mill operation results in boiler operation with fewer burning stages. In this operation, heat is released only at the highest burner stage, ensuring operational stability.	Switching to a single mill operation has resulted in reducing minimum load to 12.5% Pnom in experiments conducted in hard coal-fired thermal plants at Bexbach and Heilbronn in Germany.
Control system optimisation and plant engineering upgrade	Lower minimum load, higher ramp rate, shorter start-up time	Upgrading control systems can improve plant reliability and help operate different components of the plant close to their design limits.	Control system and engineering upgrades resulted in the reduction of minimum load from nearly 67% P_{nom} to 48% P_{nom} at two units in the Weisweiler lignite-fired plant in Germany.
		Software systems that enable dynamic optimisation of key components such as boilers can reduce the start-up time and increase ramp rate.	ABB's boiler control system software BoilerMax allows plant operators to choose between different start-up options based on market requirements.
Auxiliary firing with dried lignite ignition burner	Lower minimum load, higher ramp rate	This involves using auxiliary fuel such as heavy oil or gas to stabilise fire in the boiler. This ensures a lower stable firing rate in the boiler. Auxiliary firing can also be used for rapid increases to the firing rate, thereby enabling a higher ramp rate.	As part of Jänschwalde research project, ignition burners were used for auxiliary firing using dried lignite, which reduced the minimum load from 36% Pnom to 26% P_{nom}.
Repowering	Shorter start-up time, higher ramp rate	When a gas turbine is placed upstream of the water–steam circuit in coal-fired power plants, thermal energy from its exhaust is transferred to the feed water through heat exchangers. The additional heat source from the exhaust also helps to increase ramp rates.	At Weisweiler plant, two 190 MW gas turbines were installed. Preheating feed water with exhaust from the gas turbines increased net power from the coal-fired unit by 6.6% P_{nom}.
“New” turbine start	Shorter start-up time	This option involves starting up the steam turbine as the boiler ramps up by allowing “cold” steam to enter the turbine quickly after shutdown.	The start-up time can be reduced by 15 minutes using this approach.

Options	Flexibilisation objectives achieved	Description	Impact
Thin-walled components/special turbine design	Shorter start-up time, higher ramp rate	Using high-grade steel, thinner-walled components can be built to ensure quicker start-up and higher ramp rates compared to traditional thick-walled components.	Not known.
Thermal energy storage for feed water preheating	Lower minimum load	Heat from the steam turbine can be absorbed by feed water, thereby reducing net power. Thermal energy stored in the feed water can be discharged to increase net power during periods of high demand.	Using a hot water storage system that can operate for 2–8 hours can reduce minimum load by 5–10%, and during discharge the hot water system can be used to increase net power by 5% without increasing the firing rate.

Source: Table adapted from Agora Energiewende (2017) and Pescia (2018).

The main costs involved in achieving flexibilisation include (i) capital expenditure involved in retrofit investments, and (ii) any increase in operating costs due to increased maintenance or reduced efficiency. Other possible barriers are invalidation of service and operation and maintenance (O&M) contract guarantees from hardware manufacturers, inflexible fuel supply contracts, limited fuel storage, and training employees to adapt to flexible production mode.

A study conducted in India estimated the additional costs of refurbishment to be approximately only 5–10% of the total project cost[5] of a new or existing baseload coal plant in net present value terms, or 8–22% in levelised terms. Final costs will vary depending on other factors, such as timing of implementation, lifetime of the plant, plant load factor levels and capital expenditure incurred for flexibilisation (Sen *et al.*, 2018).

Increased flexibility of gas power plants

In the case of CCGT power plants, flexibility is restricted by the heat recovery steam generator (HRSG), the steam turbine and the balance of plant (IEA, 2018). Design and operational changes to these units can improve their overall flexibility. For instance, traditionally HRSG components are thick-walled, requiring a longer time to warm up. Replacing these with thin-walled components makes the system better-suited to handling sudden changes in temperature and, in turn, can start up in a shorter time. Similarly, component thickness can be reduced in the steam turbine to enable quicker start-up (Eddington *et al.*, 2017; Peltier, 2011). Flexible operation can also be achieved by adding a bypass such that waste heat from the gas turbine is not captured or a steam bypass from the HRSG to the condenser, which enables a CCGT plant to be operated as an OCGT plant.

However, such replacement of HRSG and steam turbine materials is a major capital project taking the plant out of service for a long time. The cost of such replacements could also be equivalent to building a new more flexible unit, which may provide significantly more operational flexibility. In addition, these changes can reduce the operating efficiency of the plan (kilowatt hours [kWh] produced per joule of energy input), thus increasing carbon dioxide intensity (kilograms of CO_2 produced per kWh). The trade-off between the gains and drawbacks in increasing the flexibility of conventional plants needs to be well assessed.

Some gas turbine vendors[6] have developed new plant designs with a higher degree of flexibility. For instance, GE has developed a gas turbine, steam turbine and an HRSG system that can provide a ramp rate of 50 MW/min, compared to the normal 10–20 MW/min, and achieve full start-up in under 30 minutes, compared to 1–4 hours for the old designs (TMI, 2016). Similarly, Wärtsilä has developed ICEs with an even higher degree of operational flexibility. Wärtsilä gas engines achieve high operational flexibility with several features, including multi-unit design, fast start-up time (5 minutes to full load from start command, and only 2 minutes in ultra-fast start) and fast ramp rate. Engine minimum load has also been reduced from 30% to 10%. These ICEs have been installed in highly granular electricity markets such as the Electric Reliability Council of Texas (ERCOT) in the southern United States (Golden Spread Electric Cooperative, 2018).

5 Incremental total project cost (in net present value terms) includes incremental capital expenditure, operating expenditure, cost due to reduced power load factor and cost due to reduced project life (Sen, Trivedi and Shrimali, 2018).

6 Such as GE, Siemens and Alstom.

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Traditionally most coal-fired generation plants have been designed to meet baseload and are not designed to be ramped up or down at short notice. Existing thermal plants' lack of flexibility to accommodate the variability of renewable energy resources can result in curtailment of VRE generation or in inefficient operation or idling of the conventional power plants (Gonzalez-Salazara, Kirsten and Prchlik, 2018).

Reduced curtailment of VRE generation

Many power systems lack flexibility and struggle to adapt to increasing levels of VRE generation. This contributes to VRE curtailment (Huber, 2017). China, for example, faced issues of VRE curtailment due in part to inflexible operation of conventional thermal power plants. In 2016 about 17% of production from wind power and 10% of solar power were curtailed in the country. Subsequently China took significant measures to reduce curtailment, which included launching an ancillary service market to encourage flexible operation of thermal plants, called the down-regulation market (Clean Energy Ministerial Campaign, 2018). In the absence of down-regulation ancillary service markets, power trading occurred only in the form of long-term and short-term bilateral contracts, which do not encourage flexible operation of thermal plants.

The need for a down-regulation market was felt the most in Northeast China, where co-generation plants generate electricity that can meet the entire region's consumption, in addition to heat. Surplus power generation necessitated the introduction of down-regulation markets for the region's thermal plants, to reduce their production during periods of surplus generation from VRE sources. As a result of these measures, curtailment of wind power was reduced to 12% and that of solar power to 6% in 2017 (Clean Energy Ministerial Campaign, 2018). Models developed as part of a study showed that increased flexibility in conventional power plants in China can reduce VRE curtailment by 30% in 2025 and 2030. The annual reduction in VRE curtailment in China is expected to be 2.8 terawatt hours (TWh) in 2025 and 15.3 TWh in 2030 (Clean Energy Ministerial Campaign, 2018).

Lowering investment required for alternative flexibility options in the short term

Deployment of different flexibility solutions is often carried out in parallel and depends on the individual circumstances and investment needs. Smaller investments into retrofitting existing thermal power plants can help avoid larger investments into other flexibility options in the short or medium term until affordable solutions are available. While investment in retrofitting must be considered on a case-by-case basis, a rough estimate suggests costs between EUR 100 per kilowatt (kW) and EUR 500/kW (Agora Energiewende, 2017). For example, engineering and control system retrofits at a plant in Germany, to reduce the minimum load by 170 MW, cost around EUR 60 million (Parkinson, 2018; Agora Energiewende, 2017).

Potential impact on power sector transformation

Flexibilisation projects have been carried out in thermal power plants located in regions where large amounts of renewable energy have been integrated into the grid. The following are examples of such projects that contributed towards achieving flexibility in their respective power systems:

- **Germany:** At the Weisweiler hard coal power plant, control systems were upgraded and software was optimised for controlling the power generation process and plant operations. These upgrades **reduced the minimum load by 170 MW** and **increased the ramp rate by 10 MW/min** in one unit (Agora Energiewende, 2017). One study found that refurbishments to increase the flexibility of an average 640 MW coal-fired power plant in Germany can result in additional **yearly earnings of EUR 4 million** before interest and tax (Klose and Prudlo, 2013).

- **Denmark:** Thermal plants and **co-generation plants in Denmark were retrofitted to integrate VRE into the grid**. Alongside electricity, the co-generation plants generate heat for district heating systems. Coal-fired co-generation plants can be used to provide flexibility by reducing the amount of heat generated in order to balance the system. These measures have aided the integration of renewable power into the Denmark's grid. With over 40% of its power from wind farms, Denmark has one of the world's highest shares of renewable energy integrated into a power grid (Clean Energy Ministerial Campaign, 2018).

- **China:** Incentivising flexible operation at thermal plants through downward regulation resulted in a **30% reduction in VRE curtailment** (IEA, 2018).

- **India:** Reducing minimum generation levels for thermal plants from 70% to 55% of capacity has **reduced VRE curtailment from 3.5% to 1.4%** and has **reduced the annual operating cost of the power system by 0.9%** (USD 311 million) (Prabhu, 2018; Vella, 2017). Reducing **minimum load to 40%** is expected to further **reduce the rate of VRE curtailment to 0.73%** (IEA, 2018).

- **United States:** On the Texas grid operated by ERCOT, electric companies are able to move to a high renewables portfolio by switching from traditional inflexible coal generation to more flexible gas-fired generation capacity. The new capacity does not operate continuously, but provides a hedge to the retail portfolio against high market prices (Golden Spread Electric Cooperative, 2018).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Overall, improving the flexibility of existing power plants is determined by plant-specific infrastructural improvements, and policy and regulatory frameworks such as economic incentives and a pricing framework for flexibility services (IEA, 2018). To encourage investment in infrastructural improvements for flexibility, the power system should provide sufficient incentive in the form of market design and pricing policies. Therefore, both aspects must work in tandem to create an ecosystem that supports flexibilisation of thermal power plants. Some of the key factors required for flexibilisation, to increase the integration of renewables into the grid, are described below.

Market design that incentivises flexible operation of power plants

More flexible thermal plants can offer a wider range of services in the day-ahead and intraday markets,[7] as well as in the ancillary service markets, thereby unlocking new revenue streams. This is, however, highly dependent on the market design in place. The higher the time granularity in wholesale markets, the more value is placed on flexibility and the higher the revenues for flexible plants (for more information please see the Innovation Landscape briefs: *Increasing time granularity in electricity markets* [IRENA, 2019b] and *Innovative ancillary services* [IRENA, 2019c]).

With a low minimum load and high ramping rates, a flexible thermal plant can participate in the day-ahead market with its minimum load and participate in the intraday trading market with the remaining capacity, where prices are usually higher (Energinet, 2018).

In the Nordic markets, power plants, including wind and solar, can place new bids on the intraday market up to 60 minutes ahead of real time and place voluntary up and down regulating bids in the regulating power market 45 minutes ahead of real time. Therefore, thermal plants with higher flexibility can use the intraday trading markets to their advantage. To reduce imbalances, however, pricing incentives need to be established (Energinet, 2018).

Increased time granularity in electricity markets, with shorter scheduling and dispatch intervals alongside gate closure closer to real time, implies varying electricity prices and incentives for the flexible operation of thermal plants. With a shorter span between gate closure and actual transactions, the forecast accuracy for VRE generation also improves, thereby reducing the amount of conventional capacity that should be held as reserves.

Capacity held as reserves cannot be released to address any flexibility needs that may occur. Hence, with shorter scheduling intervals, thermal plant capacity is locked up as reserves for a shorter period of time, thereby increasing its availability to provide energy in the real-time markets. A study of real-time market data in New York notably observed that price signals at five-minute intervals were more effective than hourly markets in shifting generation up or down (IEA, 2018) (Milligan and Kirby, 2010).

7 In the day-ahead market, contracts are made between buyers and sellers for delivery of power the next day at a set price (NordPool, 2017a). In the intraday market, buyers and sellers can trade power close to real time to balance the supply and demand of power (NordPool, 2017b).

Market rules and pricing structures in the day-ahead, intraday, balancing and ancillary service markets should be designed in such a way that they provide an incentive for flexible operation. For example, increased time granularity (5 minutes) and close-to-real-time gate closure (0–5 minutes) can send price signals that encourage rapid start-up, higher ramping rates and short minimum uptime and downtime.

Adapt contracts for thermal plant fuel supply

In the case of gas-fired power stations, fuel contracts are typically long-term take-or-pay contracts, which may restrict a power plant's ability to operate flexibly. Similarly, power purchase agreements between generators and electric utilities can be structured according to a capacity payment, which is paid on the basis of the amount of capacity kept available, thereby limiting the plant's ability to respond to flexibility requirements. These contract structures must be revised to ensure that flexible operation of the power plant is not hindered (Vithaya, 2018).

Updated standards, grid codes and market rules

With increasing VRE integration, technical standards must be updated to ensure efficient operation of the overall system. The grid code should be updated to encourage flexible operation of thermal power plants. For instance, in India the Central Electricity Regulatory Commission amended the electricity grid code to reduce the technical minimum output for an interstate generating station from 70% to 55% of the unit's installed capacity. The regulation also specifies that the thermal plants will be compensated according to the heat rate for operating below 55% of capacity,[8] and sets out a higher ramp rate, which requires retrofits at several thermal power plants. Subsequently, the National Thermal Power Corporation (NTPC), India's largest power generating company, has undertaken engineering retrofits at its Dadri power plant, and an Indo-German group is studying flexibilisation options for another thermal power plant (Powerline, 2018).

Similarly, a demonstration project establishing an ancillary service market in North East China was launched in 2014 to incentivise thermal power plants to lower their minimum load. This incentive was replicated in five other provinces across China, resulting in about 3 000 MW of down-regulation capacity during 2017. In turn VRE curtailment fell from 11 TWh in 2016 to 7.7 TWh in 2017 (IEA, 2018).

In ERCOT, Texas, market rules allow fast-starting plants to offer 10-minute contingency reserves from standby mode. Traditional thermal power plants are typically able to provide such service only as a spinning reserve (AEMC, 2017). This allows owners of highly flexible plants to provide ancillary services for the system and earn additional revenue in (non-spinning) standby mode without incurring any fuel or operational costs, thus providing an incentive for fast-start flexibility.

8 The heat rate is a common measure of system efficiency in a steam power plant. It is the amount of energy required by a power plant to produce 1 kWh of electricity.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Countries are promoting measures to increase system-wide flexibility to increase VRE integration into the grid. As one of the principal measures for enhancing system-wide flexibility, refurbishment of thermal power plants to increase their flexibility has been undertaken in plants across countries such as Australia, China, Denmark, Germany, India and the United States.

International and regional initiatives are also supporting research and knowledge-sharing in this area. The European Union has funded "Flexturbine", a project under its Horizon 2020 initiative, bringing together six European original equipment manufacturers, research institutes and universities. The objective is to improve turbine design for enhancing flexible operation of conventional thermal power plants (Flexturbine, n.d.). The Advanced Power Plant Flexibility (APPF) campaign was launched at the eighth Clean Energy Ministerial (CEM8) in 2017 in Beijing, China. It was co-led by China, Denmark and Germany. APPF aims to build strong momentum and commitment from governments and industry to implement solutions that make power generation more flexible, offering opportunities to leverage international experience for enhancing the impact of domestic policies and actions. The campaign concluded at CEM9 in Copenhagen, Denmark, and will continue as the Power System Flexibility Campaign (Clean Energy Ministerial, n.d.).

Table 3 below lists several relevant examples of projects and initiatives to increase flexibility in conventional power plants, and their impact.

Table 3 Examples of initiatives to increase the flexibility of conventional power plants

Use case	Geography	Description	Value-added/impact
Flexibilisation of NTPC plants	**India**	NTPC, India's largest power generating company, is taking measures to implement flexibility at its power plants in Dadri (490 MW) and Simhadri (500 MW) with co-operation from the Indo-German Energy Forum. NTPC is also working with USAID to implement flexibility at Ramagundam (500 MW) and Jhajjhar (500 MW). NTPC, along with VGB, EEC and Siemens, conducted test runs at Unit 6 of the Dadri plant and observed that the minimum load could be reduced to 40% (EEC Power India, 2018).	With the presence of several thermal power plants, flexibilisation measures can result in accommodating over 20% of wind and solar generation in the Indian grid (IEA, 2018) .

To be continued on p. 16.

Use case	Geography	Description	Value-added/impact
Flexibilisation of coal plants	**China**	To reduce VRE curtailment, the China National Energy Administration evaluated possible strategies to enhance power system flexibility and established targets for VRE integration and retrofitting flexibility measures in thermal plants. In 2016 a target of retrofitting 220 gigawatts (GW) of thermal power capacity was included in China's 13th Five-Year Plan for the power sector. As part of the plan, the following power sector reforms are being introduced: (i) regional co ordination of markets, (ii) removal of interprovincial trade barriers, and (iii) prevention of coal power production lock-in caused by bilateral trading contracts.	As part of the Five-Year Plan, targets were established to increase renewable capacity by 2020. China plans to increase solar farm capacity from 110 GW to 200 GW, wind capacity from 210 GW to 350 GW and bioenergy from 15 GW to 30 GW (CNREC, 2017).
Advanced gas turbine unit	**United States**	Siemens Energy will be designing and building an advanced gas combustion turbine for Duke Energy's 400 MW expansion at Lincoln County turbine combustion station. The turbine is planned to be operational in 2024.	The new technology is expected to provide flexible peaking power to accommodate variations in solar generation. This turbine is also expected to be 25% more efficient than the other 16 turbines at the plant (Downey, 2017).
Weisweiler and Bexbach power plant	**Germany**	At the Weisweiler hard coal power plant, control system upgrade and retrofit of certain plant components were undertaken at Units G and H. The two units had a capacity of 600 MW each and were used to meet baseload. ABB's software for process control systems and operational optimisation was installed to improve flexibility (ABB, 2011). In 2011 Bexbach hard coal power plant, 721 MW capacity, switched from two-mill to single-mill operation for reduced minimum load (Agora Energiewende, 2017).	Upgrades at Weisweiler power plant reduced the two units' minimum load and increased their ramp rate. The total cost of these retrofit's was EUR 125 million (Agora Energiewende, 2017). The minimum load at the Bexbach power plant was reduced from 170 MW to 90 MW.
Co-generation plant retrofits	**Denmark**	The coal-fired co-generation plant in Odense – designed to produce 350 MW power output simultaneously with steam offtake of 540 megajoules per second (MJ/s) for district heating supply – was retrofitted to lower its minimum load and increase its maximum heat output. With the existing hardware configuration, the minimum load was reduced by tuning the feed water supply.	The minimum load of the plant was reduced to 55 MW in condensing mode and 43 MW in backpressure mode. To increase its maximum heat output, the plant has developed an operation mode that allows the plant to expand its maximum heat output from 540 MJ/s to 630 MJ/s by lowering the power output. The plant can use this additional output to generate a higher profit during the winter season when power prices are low (Clean Energy Ministerial Campaign, 2018).
Smart power generation plants with ICE technology	**Texas (US)**	Denton Municipal Electric decided to close down its existing coal-fired generation plant and invest in a 225 MW smart power generation plant that uses ICEs as a flexible peaker plant to accommodate variations in renewable energy supply (Wärtsilä, 2016).	With the plant, the city aims to increase the share of power generation from wind energy.
	Australia	AGL Energy, an integrated energy company, is setting up an ICE power plant with 12 of Wärtsilä's 50DF (dual-fuel) engines, in order to respond to fluctuations due to a high share of renewable energy in the market.	A study done by Wärtsilä and Roam Consulting found that a 200 MW smart power generation plant can provide additional gross revenue of USD 8.9 million per year compared to a heavy-duty OCGT plant, which is typically a flexible plant, used as a peaker plant (Wärtsilä and Roam Consulting, 2018).

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Engineering retrofits to reduce minimum load, reduce start-up times and cost, reduce plant minimum up- and downtimes, and increase ramping rates and part load efficiencies of the thermal power plant and its key components. • The retrofits should be carried out considering the technical limits and operations of the entire plant as a whole. **Software:** • Control system and operations upgrades such as optimisation software to enable flexible operation of the thermal power plant's components (boilers, turbines etc.).
REGULATORY REQUIREMENTS	• Regulations that encourage flexible operations of thermal power plants, such as regulations specifying minimum load and ramping rates. • New ancillary service products that are valued in a high-VRE system and create revenue streams for flexible power plants. • Increased time granularity in wholesale markets, so that prices reflect close-to-real-time market conditions. • Policies to revise take-or-pay contracts with terms that encourage flexible operation of thermal plants.
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Thermal power plant generators:** • Analyse plant operation processes and identify avenues for flexible operation. • Participate in day-ahead, intraday and balancing markets in order to maximise profitability. **Government:** • Provide financial incentives for existing thermal power plants to implement flexible operation.

ABBREVIATIONS

APPF	Advanced Power Plant Flexibility
CCGT	combined-cycle gas turbine
CEM	Clean Energy Ministerial
CO_2	carbon dioxide
ERCOT	Electric Reliability Council of Texas
h	hour
HRSG	heat recovery steam generator
ICE	internal combustion engine
kW	kilowatt
kWh	kilowatt hour
min	minute
MJ/s	megajoule per secondV
MW	megawatt
NTPC	National Thermal Power Corporation
OCGT	open-cycle gas turbine
P_{nom}	nominal power
TWh	terawatt hour
VRE	variable renewable energy

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IRENA HEADQUARTERS
P.O. Box 236, Abu Dhabi
United Arab Emirates

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