Wärtsilä modular power plant comprised of multiple ICE generating units provides output flexibility.

Defining true flexibility – a comparison of gas-fired power generating technologies

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Power plant flexibility – the ability to rapidly adjust output up or down as demand and system loads fluctuate – is recognized as a vital tool to manage variable renewable energy production and provide grid support services. Wärtsilä power plants set the standard for true flexibility due to their rapid startup time, fast ramping capability and modular design.

Increasing penetration of variable renewable energy sources presents challenges for transmission grid operators to maintain electric reliability. The intermittency in wind and solar loads is managed with redundant generating capacity that can quickly respond to these fluctuations, and has predominately been served by coal and gas-fired units that are synchronized to the grid but operating at part load. Flexible power generation that can be rapidly brought online reduces the inefficiency of relying on part load operation. Two primary measures of flexibility are startup time and ramp rate. Transmission system operators define such "quick-start" or "non-spinning" reserve as generation capacity that can be synchronized to the grid and ramped to capacity within 10 minutes [1].

Whereas conventional steam cycle generators (based on the Rankine cycle) can take more than 12 hours to reach full load, gas turbines and internal combustion engines (ICEs) can be dispatched in

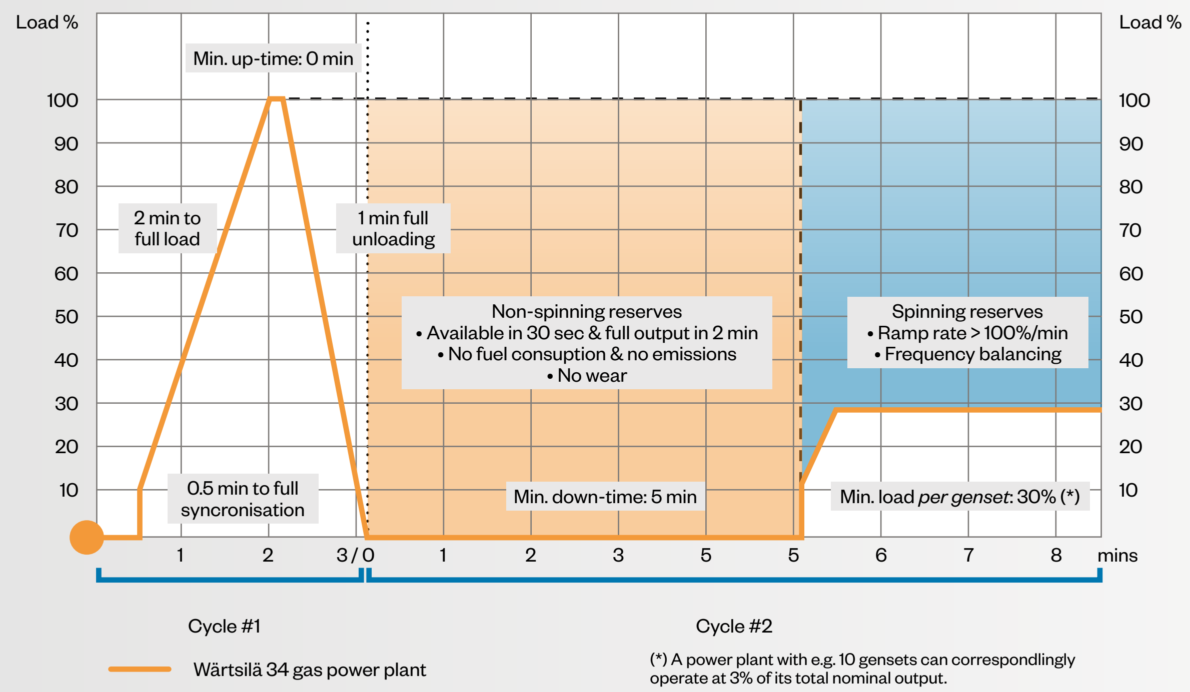

Fig. 1 – Loading and unloading of a Wärtsilä 34 gas power plant.

minutes. Startup time is a significant metric for flexibility, but comparison of different technologies and designs is complicated by the way startup time is measured by different manufacturers. The startup time quoted can be from push of the start command or from ignition. In the case of gas turbines, this difference in "start" definition can be as much as 20 minutes. Further, it is important to differentiate between the ramp time to full load versus partial load.

Gas turbine startup

During startup, a gas turbine undergoes a sequence of increasing compressor spin to reach firing speed, ignition, turbine acceleration to self-sustaining speed, synchronization, and loading. There are numerous thermo-mechanical constraints during startup of the gas turbine, including limits on airflow velocity through the compressor blades to prevent stall, vibrational limits, and combustion temperature limits to prevent turbine blade fatigue, with the significant parameter being the turbine inlet temperature.

In combined cycle operation, the heat recovery steam generator (HRSG) imposes additional thermal limitations, as the high temperature environment subjects HRSG components to thermal stress [2]. The HRSG is directly coupled to the gas turbine, so changes in turbine exhaust gases induce flow, temperature, and pressure gradients within the HRSG. These gradients must be carefully controlled to prevent adverse impacts such as material fatigue, creep (damage caused by high temperatures) and corrosion [3]. In addition, the steam turbine can restrict the gas turbine loading rate if the steam temperature leaving the HRSG exceeds steam turbine limits. To avoid this, the gas turbine is ramped to hold points (held at steady load) to allow steam temperatures and pressures to rise slowly within allowable material limits.

It takes longer to start the HRSG and steam turbine from cold conditions than from hot conditions. The definition of "hot" conditions varies by manufacturer, but is generally defined as within eight (8) to 16 hours of HRSG shutdown. As a result, the amount of time elapsed since last shutdown greatly influences startup time. Once-through HRSGs are used by some manufacturers to overcome the startup thermal and pressure limitations that exist with steam drums.

Combined cycle gas turbines (CCGTs) are also subject to purge requirements to prevent auto-ignition from possible accumulation of combustible gases in the gas turbine, HRSG and exhaust systems. The purge is required before the unit is restarted. Purge times depend on the boiler volume and air flow through the HRSG, and are typically set to about 15 minutes. This purge time adds to the overall start time.

In order to enable faster startup and ramping, CCGT manufacturers have attempted to decouple the gas turbine startup from the HRSG and steam turbine warm-up. Bypass systems are used to isolate the steam turbine, ultra-low nitrogen

oxides (NOx) combustion systems are used to reduce emissions while ramping, and attemperators maintain steam temperatures within appropriate limits [4]. A "purge credit" allows the system purge to be completed at shutdown, eliminating the requirement for a redundant purge at next startup [5]. The purge credit can only be used in some HRSGs that have no duct burners and where the gas turbine is fired on natural gas only. These improvements have resulted in higher CCGT ramp rates and startup times of about 30-35 minutes, about half the time for conventional hot start that would require purge and gas turbine holds. However, rapid cycling imposes increased CCGT maintenance costs [6]. In simple cycle, published start times for gas turbines are about 10 to 15 minutes.

ICE startup

An ICE power plant can start and ramp to full load very quickly due to rapid ignition of fuel within the cylinders and the coordinated starting of multiple generating sets. Wärtsilä ICE power plants employ high efficiency lean-burn technology that can reach full load in as little as two (2) minutes under "hot start" conditions. To meet "hot start" conditions, cooling water is preheated and maintained above 70°C, engine bearings are continuously prelubricated, a jack up pump supplies prelubrication to the generator bearings, and the engine is slow turning (cycling).

The Wärtsilä 34SG power plant requires only 30 seconds to complete startup preparations, speed acceleration, and synchronization to the grid. Loading to full power occurs rapidly in just 90 seconds. Startup time is not affected by the amount of time the unit had been previously shut down. The Wärtsilä 50SG power plant takes seven (7) minutes to reach full load. Under cold startup conditions, the Wärtsilä 34SG power plant can reach full load in 10 minutes and the Wärtsilä 50SG in 12 minutes. Flexicycle™ power plants offer advantages over CCGTs as sufficient steam pressure can be generated with only a subset of the engines operating.

Rapid startup for flexible power generation

Figure 2 shows a startup time comparison of the Wärtsilä 34SG and Wärtsilä 50SG power plants with simple cycle and combined cycle gas turbine plants from manufacturers GE, Alstom, and Siemens. All startup times are measured from operator initiation of the start sequence. As can be seen from the graph, Wärtsilä power plants provide quick start ability under 10 minutes, which meets system operator requirements. Unlike CCGTs, hot start conditions in a Wärtsilä power plant can be maintained regardless of how long the engines had previously been inactive.

Ramp rate: how fast is fast?

Because solar and wind generation can change within minutes, electric grid operators rely on dispatchable units that can provide additional load (or curtail load) on the same timescale as variations in renewable output. The increase or reduction in output per minute is called the ramp rate and is usually expressed as megawatts per minute (MW/min). Ramp rates of most industrial frame gas turbine models are advertised as 10 MW/min up to 100 MW/min, with an average of about 25 MW/min. Ramp rate depends on generating unit capacity, operating conditions (whether unit is just starting up or operating at a minimum load hold point) and optional technologies for reducing startup time and increasing ramp rate.

The ramp rate of a gas-fired power plant also depends on the number of units and configuration. For example, a ramp rate of 100 MW/min is based on multi-turbine plant designs, such as a 2x1 CCGT (net power output of 750 MW) where each gas turbine is rated to ramp at 50 MW/min. While ramp rate in MW/minute is a valuable metric, it is important to understand the operating conditions under which advertised ramp rates can be achieved.

Starting loading capability versus ramp rate

The starting loading capability is often quite different than the advertised ramp rate for gas turbines. Gas turbine ramp rates of 35–50 MW/min are achievable only after the unit has reached self-sustaining speed. The fastest loading gas turbine models produce 30 percent load delivery after 7 minutes and take nearly 30 minutes to reach full output under hot start conditions [7]. Wärtsilä 34SG engines have true quick start capability – an effective ramp rate of 50 percent per minute, reaching full load within 2 minutes. For a 200 MW plant, this equates to 100 MW/min.

The starting load delivery of Wärtsilä power plants and gas turbines is compared in Figure 3, showing the percentage of load delivered 7 minutes after startup. This assumes optional gas turbine technology for enabling fast loading and is based on manufacturer-published ramp rates. The fast startup time of Wärtsilä ICE provides a significant operational advantage over gas turbines. As gas turbines are just producing output, both the Wärtsilä 34SG and Wärtsilä 50SG engines have already reached full load.

Operational ramp rates of Wärtsilä engines and the most popular industrial frame gas turbine models of similar size (200 MW) are compared in Figure 4, with ramp rate expressed in two metrics – MW/minute and percent of full load per minute. Once running and at nominal operating temperatures, Wärtsilä power plants can adjust output up or down rapidly. Wärtsilä power plants can ramp from 10 percent to 100 percent load (or down) in just 42 seconds. This means that a power plant comprised of 12 Wärtsilä 50SG engines has an effective operational ramp rate of 288

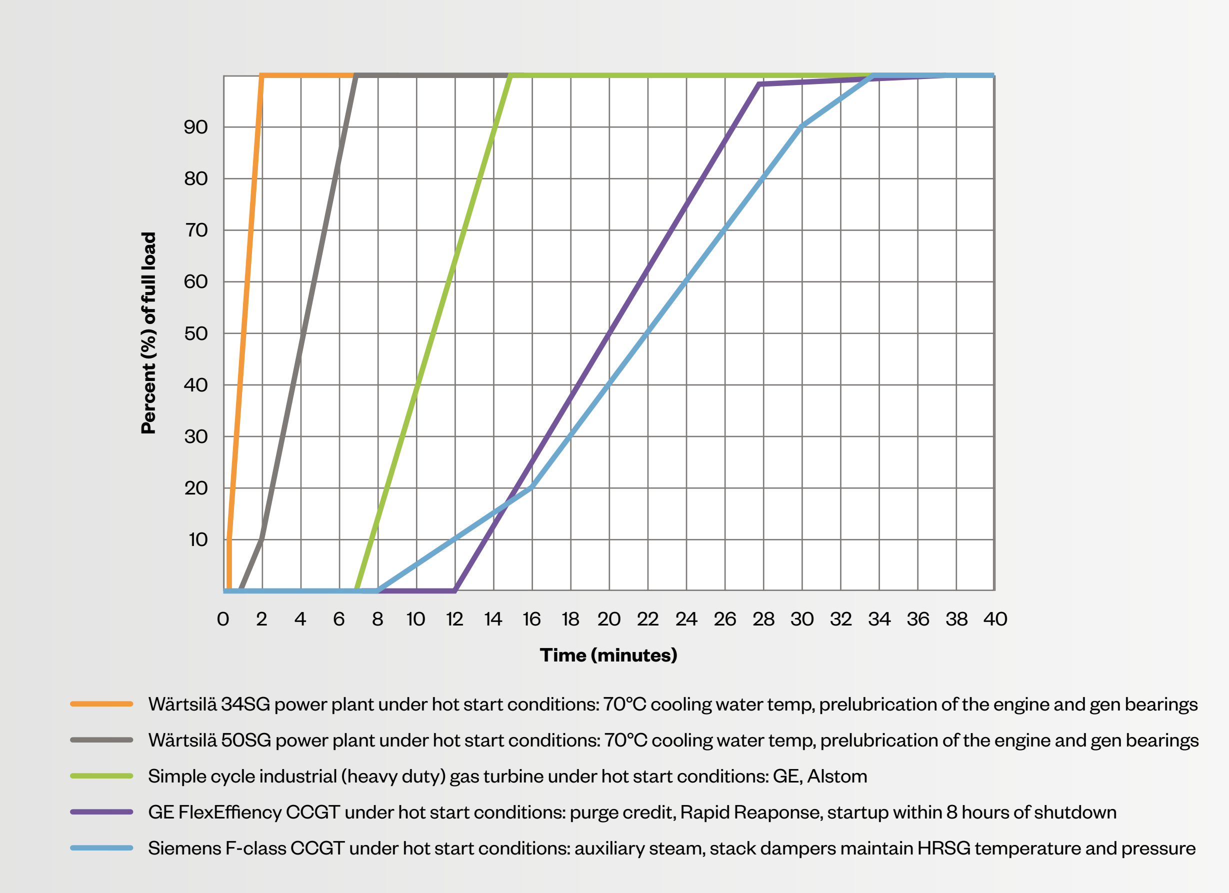

Fig. 2 - While combined cycle gas turbines can take over 30 minutes to start, Wärtsilä ICE power plants can start and reach full load in less than 10 minutes.

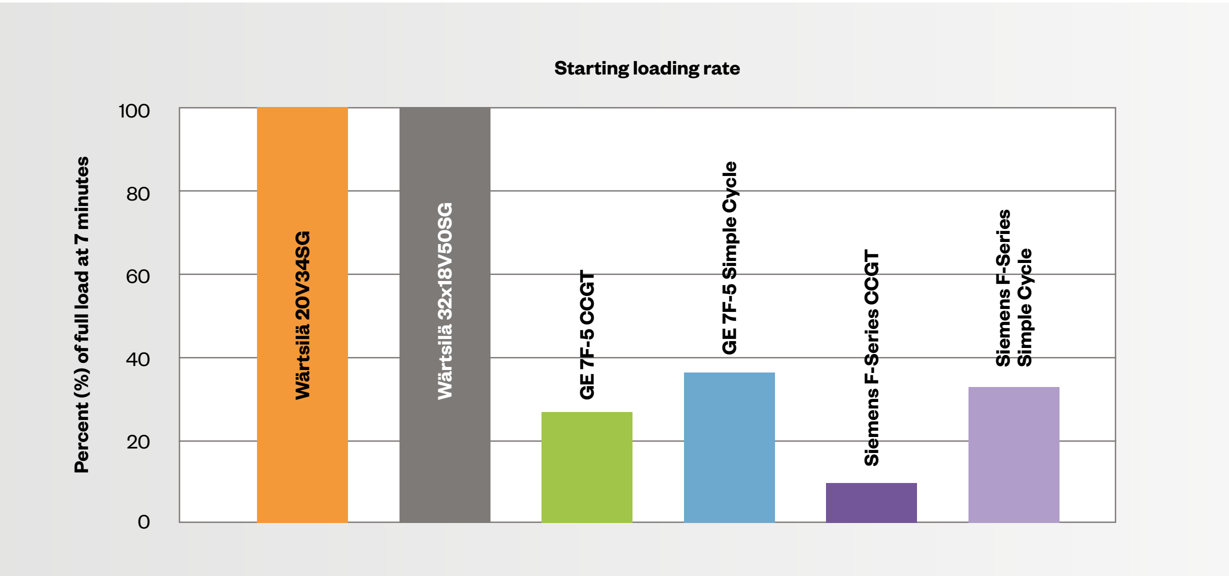

Fig. 3 - Wärtsilä power plants have a rapid starting capability, delivering full load in 7 minutes or less. The effective starting ramp rate of gas turbines is much lower, delivering only partial load in that time.

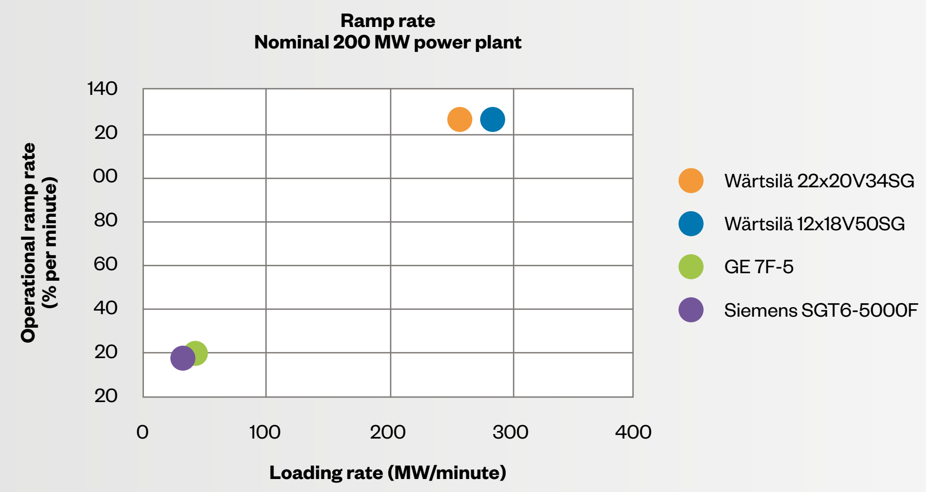

Fig. 4- Wärtsilä engines have a significantly higher operational ramp rate than gas turbines of similar size.

MW/minute – significantly faster than a comparably sized gas turbine.

Economies of numbers provides greater flexibility

Over the course of a century, the trend in the electric power industry had been toward ever increasing generating unit sizes and plant capacities. Centralized power plants were built using custom-engineered technology of massive size. Conventional wisdom was that "bigger is better" as the capital costs per unit of capacity and production costs declined with increasing unit size, delivering economies of scale driven in part by improved steam turbine efficiencies.

The push for higher outputs and efficiencies directly led to the development of combined cycle, necessitating larger gas turbines with higher firing temperatures that enabled exhaust gas heat recovery to drive a steam turbine. While in the 1950s the firing temperature of gas turbines was about 800°C and average turbine size was around 10 MW, by the 1990s advanced gas turbines averaged over 100 MW and had firing temperatures exceeding 1300°C.

However, large gas turbines required considerable on-site construction and assembly, and could not easily adjust load to meet fluctuating demand. Modularized smaller-scale generating units operated in parallel and deployed as needed to match the changing power requirements began to serve an important function for the stability of electric transmission grids. This shift toward "economies of numbers" provides reliability, construction, and efficiency benefits.

ICEs are ideally suited to modular use, as sets of 4 – 30 MW engine units can provide a range of incremental part load power without sacrificing efficiency. For example, a Wärtsilä power plant that has 28 modular Wärtsilä 34SG engine units, each sized at approximately 10 MW, can deliver a range of output from just a few MW to over 270 MW. Due to the modular design of Wärtsilä power plants and rapid startup, the engines can be loaded and unloaded individually. By operating only a subset of the engines at full load to produce the desired output, high efficiency is maintained.

Modularity offers simplified maintenance features and quality benefits, as components are prefabricated in a factory-controlled environment and tested. Prefabricated power generation modules are self-contained components of the system that are designed to interface with auxiliary power plant systems. As a result, the timeframe to plan, engineer and construct a power plant is shortened.

Because generating units are incrementally sized, a wide range of plant capacities and fuel options – including multi-fuel use – can be designed. Expanding power needs in the future can be met with the addition of more engine units and ancillary modules, rather than the construction of a new power plant. Wärtsilä ICE modularity provides built-in redundancy in case of unit outages or maintenance without significantly affecting overall full plant output.

Limitations to gas turbine flexibility

Gas turbine power plants, which have traditionally required significant on-site assembly, have begun to be designed in a modular fashion to shorten construction time. Modularity in architecture provides limited operational flexibility for gas turbines, however. This is due to the size of units, small number of units, and efficiency tradeoffs for simple cycle versus combined cycle.

Industrial gas turbines for power generation may be 100 – 350 MW apiece and have limits on the lower range of output at which they can operate. This minimal load, or "turndown" percentage, is bounded by emissions limits. When the gas turbine operates at low load, the compressor airflow may not be enough to support conversion of carbon monoxide (CO) into carbon dioxide (CO_2) in the combustion chamber. Gas turbines are generally constrained to a turndown of 30 to 40 percent of full load to meet emissions regulations [8]. A simple cycle power plant with two gas turbines can

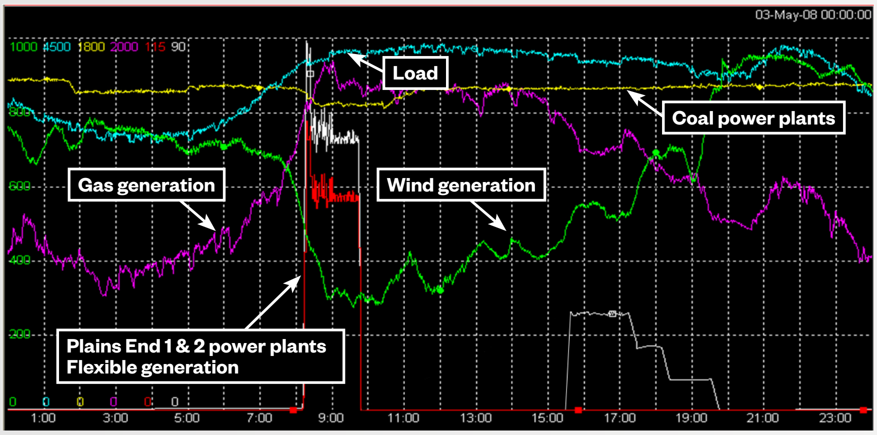

Fig. 5 - Screen shot from a dispatch center shows the drop off in wind generation (green line) and rapid ramp up of Plains End power plant to compensate. Compared to the fast ramping of the Wärtsilä plant, gas turbine output (purple line) increases more slowly (Source: Colorado Dispatch Center, Xcel Energy, USA).

adjust plant output down to about 15 to 20 percent of full load by operating only one turbine, but efficiency is limited to about 30 percent.

Combined cycle operation introduces more complexity into the operating parameters of the gas turbine plant. Modular architecture for CCGT power plants consists of one to four gas turbines, HRSGs for each gas turbine, and a common proportionally-sized steam turbine. The lower load limit is affected by the turbine exhaust temperature, which must be high enough to generate sufficient steam pressure in the HRSG to power the steam turbine. Emissions-compliant turndown for CCGT plants is usually 40 to 50 percent of full load. For example, a combined cycle power plant design based on 200 MW gas turbines (in a 2x1 configuration) has a rated output of over 600 MW, limiting turndown ability to about 300 MW. In comparison, a Flexicycle power plant based on Wärtsilä ICEs does not have similar restrictions on load turndown because sufficient steam pressure can be developed by operating only 25 percent of the engines.

Actual performance demonstrates true flexibility

Wärtsilä ICEs are perfectly suited to cycling, as the ability to quickly startup and ramp up or down in load does not affect the maintenance schedule. In addition to a fast startup time, Wärtsilä engines can stop within one minute and have lower emissions due to lean-burn technology. The difference in performance between gas turbines and Wärtsilä power plants is evident in Figure 5, which presents a screen shot from an actual dispatch center in Colorado, U.S. The Plains End power plant units (red and white load curves) were used to compensate for a sudden drop off in wind output, rapidly starting and ramping to full load within minutes. By contrast, gas turbines (purple load curve) ramped up at a much slower rate from a low load. This underscores that advertised ramp rates and startup times do not always reflect operational capability, and illustrates the true flexibility provided by Wärtsilä power plants.

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