Increased efficiency and flexibility of large coal-fired power plants applied to 350-MW-class units

Thomas Achter, Dr. Rainer Quinkertz and Matthias Baca

Siemens AG, Germany
Abstract

Power generation fired on carbon-based fuels places high priority not only on profitability, but also on responsible fuel handling and consumption. Efforts to reduce CO₂ emissions undertaken in the past have focused on large, state-of-the-art steam power plants in the higher output classes.

As a result, measures aimed at increasing efficiency and flexibility were developed for large units.

The Organisation for Economic Co-operation and Development (OECD) recently addressed the environmental requirements as a precondition for export financing for the entire range of coal-fired power plants.

Going forward, the good experiences gained from existing high-end ultra-super critical (USC) coal-fired power plants needs to be transferred to power plants of the 350-MW size. Innovative products are needed to serve this market segment in the most beneficial way for power plant owners. Siemens has modified its core components to address these new requirements while bringing added value to our customers.

Siemens’ steam turbines demonstrate how technology for (U)SC applications in larger units have been introduced in proven turbine designs for subcritical applications.

For steam turbine generators, Siemens is leading the way with an innovative mix of proven components and technologies to reduce initial, operational and service costs and provide top performance with operational flexibility.
Table of content

Contents
Abstract .......................................................................................................................................................... 2
Table of content ........................................................................................................................................... 3
1. Efficiency, flexibility and CO₂ reduction as market drivers for competitive power plants ................................................................................................................................. 4
  1.1. The concept of faster, higher, further initiated focused on the largest units ............ 4
  1.2. OECD financing rules ................................................................................................................. 5
  1.3. Market situation and consequences for small steam power plants ..................... 6
2. Historical development ...................................................................................................................... 7
  2.1. Steam parameters .................................................................................................................... 7
  2.2. Flexibility ................................................................................................................................... 8
3. State-of-the-art ultra-supercritical (USC) steam turbines .............................................. 9
  3.1. Upgrading a combined high and intermediate pressure (HI) steam turbine module ................................................................................................................................. 9
  3.2. Steam turbine flexible operation ......................................................................................... 11
  3.3. Steam turbine efficiency ...................................................................................................... 11
  3.4. Turbine CAPEX and OPEX ................................................................................................. 12
4. Siemens’ current and future generator portfolio ................................................................. 13
  4.1. Generator requirements and technology ....................................................................... 16
  4.2. Generator efficiency ........................................................................................................... 17
  4.3. Generator CAPEX and OPEX .......................................................................................... 18
5. Conclusion ......................................................................................................................................... 19
  5.1. Optimum economical value through increased power density ............................. 19
  5.2. Ideally suited to meet market requirements – efficiency, flexibility and reliability 19
6. References ........................................................................................................................................... 21
1. Efficiency, flexibility and CO₂ reduction as market drivers for competitive power plants

Historically, financial business cases have been the basis for developing product efficiency improvements. Higher first-time investment for improved steam parameters had to be paid back in the form of lower fuel consumption over a certain timeframe. Furthermore, government regulations that could lead to possible reductions in plant efficiency due to more stringent emissions limits governing DENOX and desulfurization, etc., needed to be compensated for.

The rise of renewable energy such as wind and solar power is forcing fossil fuel power plants to assume the role of covering the residual load. Due to the limited predictability renewables and the current lack of large-scale energy storage capacity for wind and solar power, highly demanding load change rates occur in power grids utilizing a significant fraction of renewable energy.

As CO₂ is considered a contributor to global warming, particular product development effort is focused on reducing CO₂ impacts around the world.

1.1. The concept of faster, higher, further initiated focused on the largest units

The development of power plants has typically followed the system of best economical value. Large-scale units have a better $/kW ratio than small units. The application trend therefore shifted to larger units for simple economic reasons. Implementing improved technology with the potential of lowering operating expenditure (OPEX) yielded greater benefits in large-scale units. Following this logic, developments aimed at the highest ultra-supercritical (USC) steam parameters were introduced into large, state-of-the-art power plants of the 660- to 1000-MW range. Smaller units followed this trend to
optimized capital expenditure (CAPEX), which resulted in many projects in this output class remaining at subcritical steam conditions.

1.2. OECD financing rules
The more stringent financing rules introduced by the OECD in November 2015 have strongly impacted the aforementioned methodology, requiring changes in the marketplace. The conditions of these new financing rules are summarized in the table presented below as Figure 1.

<table>
<thead>
<tr>
<th>PLANT UNIT SIZE (gross installed capacity)</th>
<th>Unit &gt; 500 MW</th>
<th>Unit 300 to 500 MW</th>
<th>Unit &lt; 300 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-supercritical (i.e., with a steam pressure &gt;240 bar and ≥593°C steam temperature), OR Emissions &lt; 750 g CO₂/kWh</td>
<td>12 years¹</td>
<td>12 years¹</td>
<td>12 years¹</td>
</tr>
<tr>
<td>Supercritical (i.e., with a steam pressure &gt;221 bar and ≥550°C steam temperature), OR Emissions between 750 and 850 g CO₂/kWh</td>
<td>Ineligible</td>
<td>10 years, and only in IDA-eligible countries¹,²,³</td>
<td>10 years, and only in IDA-eligible countries¹,²,³</td>
</tr>
<tr>
<td>Subcritical (i.e., with a steam pressure &lt;221 bar), OR Emissions &gt; 850 g CO₂/kWh</td>
<td>Ineligible</td>
<td>Ineligible</td>
<td>10 years, and only in IDA-eligible countries¹,³</td>
</tr>
</tbody>
</table>

Figure 1: Framework conditions for OECD financing, depending on technology (source OECD)
This implies that steam power plants in the 300- to 500-MW range need to be supercritical or ultra-supercritical units in order to receive attractive financing.

1.3. Market situation and consequences for small steam power plants
A significant number of projects in the 350-MW class are forming, driven by various factors. New unit business is quite heterogeneous on the one hand, consisting of diverse projects all over the world where size is limited due to grid restrictions or island operation. On the other hand, however, there are numerous repowering projects in which old units are to be replaced with new, more efficient equipment using available infrastructure.
2. Historical development

Due to the technology available at the time of application, the individual components utilized in these power plants were of similar character across the entire market.

2.1. Steam parameters

Steam turbine applications and their performance have been continuously improving ever since the steam turbine was first invented. Figure 2 below shows the development of steam inlet temperatures, main steam pressure, power output and thermal efficiency since 1960.

![Graph showing development of steam parameters](image)

Figure 2: Development of state-of-the-art technical parameters of steam power plants since 1960

While the rise in steam temperatures has always required new material developments, increasing power output and main steam pressure has to a great extent required improved mechanical design with existing materials. This is why efficiency, in the past,
was first driven by pressure increase up to supercritical conditions. It was possible to raise steam temperatures up to 600°C and reach ultra-supercritical parameters after the development of high chromium steels.

Figure 2 shows the state-of-the-art parameters. For overall economic reasons, steam power plants in the 350-MW class have until recently remained subcritical, with temperatures not exceeding 566°C.

2.2. Flexibility

Power generation has typically consisted of units operated in steady-state condition with low load change rates. The currently ongoing worldwide expansion of electricity production from renewable energy sources requires a wholly different operating regime for fossil fuel power plants, which are now called on to generate the residual load in the grid.

According to the merit order, gas-fired power plants are the first type of power plants that have to be shut down once renewables are brought on line. Following that logic, the initial approach has been to accommodate high load change rates by bringing on line and taking off line those combined-cycle power plants that were first to adapt to achieve fast startup and shutdown times.

With the increasing volume of renewable energy available, coal-fired power plants are now experiencing the same requirements as gas-fired units. The know-how gained from the water-steam cycle of combined-cycle power plants is now enabling engineers to adapt steam power plants to meet these challenging requirements.
3. State-of-the-art ultra-supercritical (USC) steam turbines

Siemens, together with its licensees in China, India and Japan, is the worldwide technology leader for steam turbine generators and has the world’s largest installed fleet.

As described in Section 2.1 above, the main steam pressure of today’s steam power plants is typically above 160 bar, and the steam cycle includes reheat capacity. Provided that the condenser cooling temperature is not too low, these conditions result in steam turbines in the power output range of 250 to 750 MW equipped with two or three turbine sections. This means that the high-pressure (HP) and intermediate-pressure (IP) turbine sections can be separate turbine cylinders or combined in a single casing. Generally, a two-casing design results in lower product costs than a three-casing design. Excellent operating experience is currently available from individual HP and IP turbine modules capable of operating at USC parameters. This reference of steam turbine design in terms of high performance parameters and high operational flexibility was used to extend the available subcritical combined high- and intermediate-pressure (HI) steam turbine to supercritical parameters. In the typical power output class around 350 MW, a two-casing design can achieve turbine efficiency rates similar to those of a three-casing design.

3.1. Upgrading a combined high and intermediate pressure (HI) steam turbine module

As explained above, recent changes in the power plant market require supercritical steam turbines in the 350-MW class as well. Figure 3 below shows Siemens’ design of an HI turbine. Details of this proven product are provided in References [1] and [2].
One major characteristic feature of this design is its integral inner casing. That means that the inner casing consists merely of one upper section and one lower section which are horizontally flanged. This design enables in particular the lowest radial and axial clearances, which translates into minimum losses. The major challenge has always been to prevent or rather manage the steam leakage across the horizontal joint. Based on the extensive experience and validation of this HI turbine design and using state-of-the-art design analysis methodologies such as the finite element method (FEM) and computational fluid dynamics (CFD), the inner casing wall thickness has been increased locally to enable supercritical inlet pressure. What is more, the size and number of joint bolts have been optimized. Another focal point for the design has been the piston sealing between the high- and intermediate-pressure inlet section. As a result, the upgraded turbine module is now applicable for supercritical pressure in a power output range of 250 to 500 MW, and delivers an inner efficiency as high as designs with separate HP and IP turbine modules.
3.2. **Steam turbine flexible operation**

Following the proven design concept for HI turbines, the upgraded version for supercritical pressure can also be operated with maximum flexibility as described in Reference [1]. For startup, for example, it is only temperature differences in the turbine rotor which may limit the maximum load ramp, i.e. even with the increased pressure the turbine casing remains unaffected. All of the most effective, proven flexibility features can be applied in the supercritical turbine, such as fast startup mode, early steam admission (parallel startup and co-start) and the various measures for frequency support.

3.3. **Steam turbine efficiency**

Apart from the efficiency benefit resulting from the integral inner casing described in Section 3.1 above, the following design features contribute to the high thermal performance of the HI turbine:

- The complete outer surface of the inner casing is exposed to IP exhaust steam, which has the lowest temperature available in the HI turbine. Therefore no external cooling steam is required and associated losses are prevented.
- The main steam and reheat valves are directly flanged to the outer casing, i.e. minimum flow reversal is achieved.
- Because of the full arc admission, flow losses are minimized in the inlet section.
- Customized 3D reaction blading maximizes efficiency on a project-specific basis.
- The single bearing between the HI and LP turbine sections minimizes friction losses.
3.4. **Turbine CAPEX and OPEX**

Besides the high performance and flexibility outlined above, the HI turbine provides additional advantages not only in terms of maintenance, but also with regard to integration into the overall power plant. Due to the fact that the main steam and reheat valves are flanged to the lower part of the HI outer casing, only the cross-over pipe to the LP turbine has to be disconnected before the upper turbine casing can be removed. In addition, the overall length of the turbine train is reduced to a minimum, which means the turbine foundation, too, and ultimately the entire turbine building can be as compact as possible. The reduced number of bearings leads also to less foundation costs. In terms of the required target heat rate, it is possible to equip the steam turbine with either one or two main steam valves. Main steam piping costs can be reduced if only one main steam valve is provided. Like all Siemens utility steam turbines, the new supercritical HI module also adapts to the inspection intervals of 50,000 hours for medium inspections and 100,000 hours for major inspections. That means that first opening of the turbine casing need not be undertaken until after approximately 12 years of operation.
4. Siemens’ current and future generator portfolio

Siemens is a world leader in electrical generator technology and manufacturing with long standing tradition and experience, and a vast installed fleet.

Throughout the years, products have been designed by developing new technologies and implementing innovations step by step in such a way as to maximize performance and achieve significantly higher product utilization levels.

This successful approach has resulted in Siemens’ current generator product line that consists of three major machine classes:

- SGen-100A: Air-Cooled Line
- SGen-2000H: Hydrogen-Cooled Line
- SGen-3000W: Water-Cooled Line

Even though today’s generator product lines from Siemens have been very successful and are highly regarded by customers, changes in market requirements and conditions are driving continuous improvement and innovation.

As a response to the ever changing market dynamics, Siemens is constantly working on developing new products and solutions.
SGen-2000P will replace traditional indirectly cooled hydrogen generators.

Air-cooled generators and water-cooled generators currently form a standard Siemens product line and represent a significant portion of the Siemens fleet, with hundreds of machines installed worldwide. Air-cooled generators have an excellent track record in terms of robustness, reliability and low operational cost, while Siemens’ water-cooled generators provide the highest output capability in the industry. Building on the success of these air-cooled and water-cooled units, Siemens continues to innovate and develop new products offering the highest level of modularity, robustness and operational flexibility. Figure 4 above provides a side-by-side comparative view of our existing and future generator portfolios. Combining air cooling and water cooling is the latest product innovation step bringing added value to our customers.

The result of this next innovative step is the development of the SGen-2000P line of Siemens pressurized air-cooled machines. This new product line is set to replace the
indirectly hydrogen-cooled SGen-2000H series, and will become a standard product in future Siemens gas turbine and steam turbine packages. The new pressurized air-cooled electrical generator combines decades of successful design, manufacturing and operational know-how to provide an innovative product with immediate customer benefits. Eliminating hydrogen gas auxiliary systems significantly reduces plant operation and maintenance costs. Figure 5 provides an overview of how the auxiliary systems are simplified. The next generation of Siemens generators represents a platform well-prepared to meet future market challenges.

Figure 5: SGen-2000P reduction of auxiliary systems compared to H₂ cooled generator
4.1. **Generator requirements and technology**

Globally expanding utilization of renewable energy has a significant impact on the operating regimes in conventional power plants. Power supply from renewable sources is not constant, which creates the need for additional operational flexibility in modern gas and steam turbine power plants. Today's turbine-generator shaft train components are exposed to extremely volatile operating modes with a high number of start/stop cycles, numerous steep load ramps, frequency and voltage fluctuations. As a consequence, thermo-mechanical stresses and accelerated aging of the shaft train components, including generators, must be considered in the design to avoid unexpected costs and extensive outage periods.

Changing market requirements are addressed in the new Siemens generator portfolio. One of the most critical generator components in terms of thermo-cycling is the stator winding. The high-voltage insulation system in particular must be extremely robust and capable of withstanding frequent cycling stresses. The SGen-2000P generator features the Siemens GVPI (Global Vacuum Pressure Impregnation), Micalastic System. The robust and proven GVPI Micalastic System satisfies the changing market operating trends by implementing an inner corona protection design (ICP) between the copper strands and main insulation and by a double layer outer corona protection design (OCP) between the main insulation and laminated core. Both interfaces are free of electrical stress, which prevents the occurrence of partial discharges.

In addition to its GVPI Micalastic insulation system, the SGen-2000P features a water-cooled stator winding which provides additional mitigation for further cyclic thermal stress reduction. The cooling water circulates through the winding in stainless steel tubes that are significantly less sensitive to water chemistry and additionally contribute to the robustness of the whole system. By applying these design features, thermo-mechanical stresses are decreased significantly and the consequential impact on
generator lifetime consumption is minimized. The incorporation of existing product know-how into the 2000P generator is highlighted in Figure 6 below.

4.2. Generator efficiency

The SGen-2000P generator is fully optimized for application in today’s steam turbine and gas turbine power plants. Replacing hydrogen cooling with pressurized air significantly reduces plant complexity and eliminates explosion safety concerns. Implementation of innovative design features and load-dependent air pressure control enable the SGen-2000P technology to achieve efficiency levels comparable to indirect hydrogen-cooled generators, see Figure 7.

<table>
<thead>
<tr>
<th>2000P</th>
<th>P = 350 MW</th>
<th>P = 350 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>p.f</td>
<td>0.8</td>
<td>0.85</td>
</tr>
<tr>
<td>η [%]</td>
<td>98.81</td>
<td>98.96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2000H</th>
<th>P = 350 MW</th>
<th>P = 350 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>p.f</td>
<td>0.8</td>
<td>0.85</td>
</tr>
<tr>
<td>η [%]</td>
<td>98.84</td>
<td>98.94</td>
</tr>
</tbody>
</table>

Figure 6: SGen-2000P Overview & benefits, an innovative mix of Siemens technology

Figure 7: SGen-2000P generator efficiency compared to current design
4.3. **Generator CAPEX and OPEX**

The SGen-2000P generator was designed with particular focus on service and maintenance. Along with eliminating hydrogen-related generator auxiliaries, numerous service-friendly design solutions have been implemented. This approach yields numerous benefits and will create substantial value for generator operators and end-customers.

The SGen-2000P generator line features the following operational benefits:

- Significantly reduced number of components to be disassembled and inspected, including bearing brackets, H₂ shaft seals, gaskets, piping and auxiliary systems, etc.
- No degassing needed after shut down and refilling of H₂ before restart
- No air leakage test after inspection or minor corrections such as rebalancing
- Simplified realignment due to bearing pedestals, and no need for pressurizing the frame (end-shield deflection)
- Improved access to end windings – reduced service duration
- No hydrogen seal replacement at the rotor winding leads (radial bolts)
- No gas baffles at the rotor end winding – no risk of breakage, and easier inspection
- Simple sensor wiring without hydrogen – no gas-tight terminal board, no explosion hazard area
5. Conclusion

In our modified steam turbine-generator set SST-PAC 5000 for 350-MW applications, we have selected all features from various product lines. Large coal-fired steam power plants delivered the proven technology for the best possible efficiency and some proven flexibility features. Steam turbine-generator sets for combined cycle power plants provided the proven technology for highest possible flexibility. For, after all, Siemens’ outstanding quality stands for highest reliability.

5.1. Optimum economical value through increased power density

For the power output class of 350 MW, Siemens decided in favor of a two-casing steam turbine design consisting of a combined HP/IP steam turbine section and a low-pressure (LP) turbine section. This reduces overall turbine building length and eliminates an additional bearing. Siemens’ proven generator technologies have enabled Siemens to build a reliable generator in that output range without the need for hydrogen cooling, thereby benefiting the customer in terms of safety and total cost of ownership (installed and operational). Furthermore, the planning and erection effort for this component solution is minimized compared to conventional three-casing steam turbines with a hydrogen-cooled generator and auxiliaries.

5.2. Ideally suited to meet market requirements – efficiency, flexibility and reliability

All in all, Siemens is able to provide flexible products which give our customers clear competitive advantages:

- Highest efficiency to
  - Reduced fuel cost
Enjoy the best reputation among the energy community and population at large in CO₂ reduction

- Fastest on the grid to
  - Participate in flexibility market
  - Actively support expansion of renewable energy

- Highly reliable to
  - Get the best value and return on your investment
  - Ensure dependable electricity production
6. References
