

Balancing economics and environmental
friendliness -
the challenge for supercritical coal-fired power
plants with highest steam parameters in the
future

Jens Rosenkranz, Dr. Andreas Wichtmann
Siemens Power Generation (PG),
Germany

Introduction

The development of coal fired power plant technology can be described as an evolutionary advancement towards greater power output per unit and higher efficiency. Higher power output per unit is based on improved and new materials which are capable of sustaining higher stresses and enabling the design of e.g. bigger turbine modules and last stage blades. Higher power plant efficiency has been and will be achieved by e.g. improving turbine and boiler efficiency by increasing the maximum steam parameter to supercritical and ultra-supercritical conditions and by reducing of mechanical and thermodynamically losses. Ultra-supercritical steam conditions are characterized by >250 bar and 600°C main steam and > 600°C reheat steam conditions. The maximum temperature and pressure for ultra-supercritical application which can be handled by state of the art turbine design and material features of 300 bar and 600°C main steam and 620°C reheat steam conditions.

On the basis of this steam conditions the overall net efficiency can reach values of up to 48 percent, depending on location and further efficiency increasing measurements.

The increase of efficiency given by a continual development of turbines was considered in the concept study Reference Power Plant North Rhine-Westphalia¹ an optimized turnkey hard coal power plant [1].

Siemens has developed for the European power market a 600 MW single unit concept together with several partners. This plant concept fulfils the requirement to balance reliable power supply, sustainable use of existing resources and economic operation. The Reference Power Plant NRW (RPP NRW) is designed for an inland location and achieves a net efficiency of 46 %.



Figure 1: Reference Power Plant North Rhine-Westphalia

¹ The study was supported by funds provided by the German Federal State of North Rhine-Westphalia (European Regional Development Fund – ERDF) [registration number 85.65.69-T-138]

This paper will describe results of the turbine development. Some special aspects of the water steam cycle optimization of the concept study Reference Power Plant North Rhine-Westphalia will be given. Results of the boiler optimization are published in the concept study [1] itself or other papers e.g. [2].

Furthermore a view in the future of steam power plants will be given.

Steam Turbine Design for highest steam parameters

The design of a steam turbine set for an ultra-supercritical application depends on the number of reheats selected, unit rating and site backpressure characteristics. For a single reheat and a power output in the range of 600-

1000 MW a typical turboset design will consist of three separate turbine modules operating at different pressure and temperature levels.

These modules are the high pressure turbine (HP), the intermediate pressure turbine (IP) and up to three low pressure turbines (LP). The generator is directly coupled to the

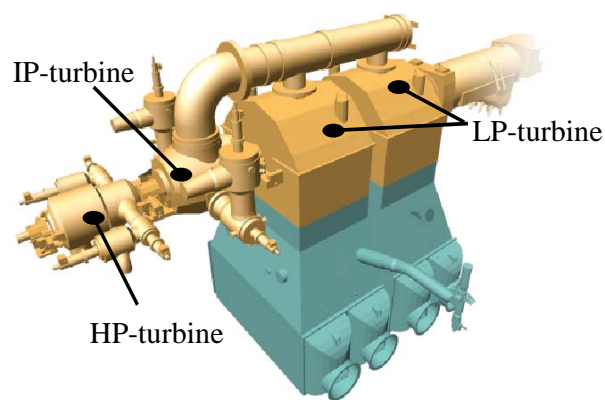


Figure 2: 600-1000MW-class turboset

last LP turbine (Figure 2). These features are well known from former supercritical applications built in the 1960's but have to be adapted to today's design principles and unit sizes.

Applying the results of state of the art material research steam temperatures of about 300 bar / 600°C for the HP turbine and 620°C for the IP turbine are applied today.

To further increase the steam parameters up to approximately 300 bar / 650°C life steam conditions the additional utilization of certain design features such as active cooling of high temperature components and the introduction of new materials is necessary.

Going to even higher steam temperatures of 350 bar / 700°C will result in an overall power plant net efficiency of more than 50 percent. This can be achieved by modification of design principles and the use of super-alloys for all high temperature parts of HP und IP turbine [3].

High pressure turbine

The basic design principle for the HP turbine which is capable to cope with ultra-supercritical main steam conditions is the barrel type outer casing design. Today this design can enable 300 bar and 600°C. The HP turbine is shown as a cross-section in Figure 3. The high temperature components such as the inlet barrel, rotor and inner casing are made out of 9-12 % CrMoV steel.

The barrel type outer casing has a vertical casing split which can handle highest pressure loadings by adopting the wall thickness. This design without a horizontal flange results in an optimal thermal deformation behavior. The benefit are small radial clearances between inner casing and blades, which means best turbine efficiency.

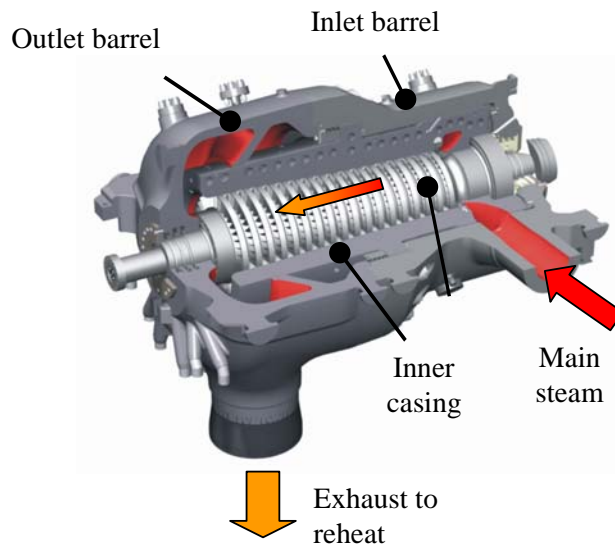


Figure 3: Barrel-type high pressure turbine (HP)

Intermediate pressure turbine

The IP turbine is designed to take reheat steam conditions of 620°C, Figure 4. In figure 4 is shown a single IP turbine with double flow exhaust design. The rotor and inner casing are made of 9-12 % CrMoV-steel. The high steam temperature can be handled by reducing the rotor surface temperature by the principle of Vortex cooling. This cooling principle enables a temperature decrease due to the reduction of relative steam velocity at the rotor surface up to 20 Kelvin.

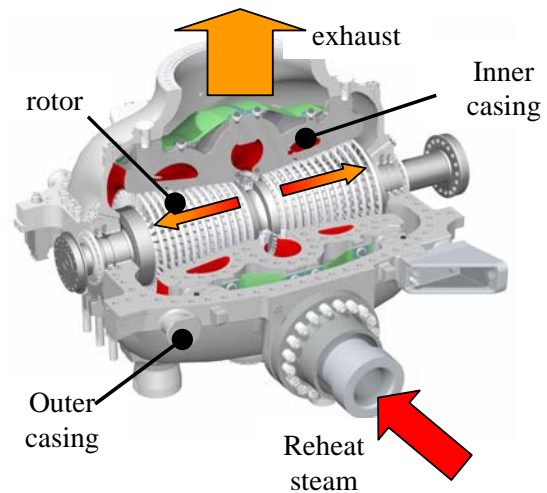


Figure 4: Intermediate pressure turbine (IP)

In addition the first blade stages are made of Nickel-based-alloyed steel to withstand the centrifugal load in combination with high temperatures.

Low pressure turbine

The exhaust steam of the IP turbine enters via a single cross over pipe the LP turbine, Figure 5. The LP turbine consists of a double flow with a horizontal split casing. The typical steam conditions are up to 7 bar and 350°C. The steam will expand to the condenser at condenser pressures in the range of 30 - 100 mbar. Because of the high volumetric flow rates special care has to be attributed to the appropriate choice of LP turbine exhaust area and design.

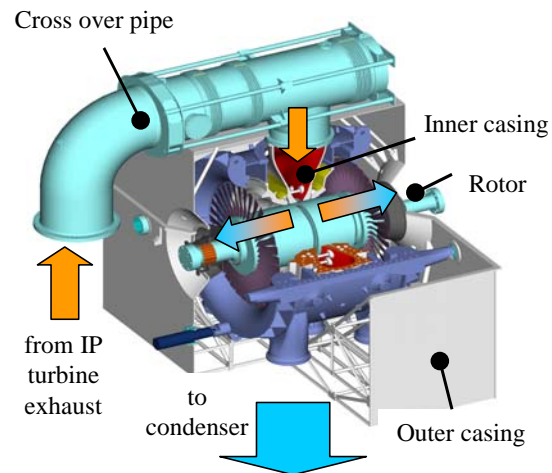


Figure 5: Low pressure turbine (LP)

The development of optimal last stage blade families and long last stage blades is the key for reasonable exhaust areas, i.e. reduced exhaust losses.

Reference Power Plant North Rhine-Westphalia - Basics

The objective of power plants within today's market boundaries is more than ever to ensure high efficiency (to reduce the environmental impact as much as possible) while at the same time to increase their economics in competition to existing alternatives.

The development of an economical and efficient concept needs to look at the steam turbine all other main components like boiler, flue gas cleaning equipment and the optimization of the water-steam-cycle as main parts for the optimization.

The developed RPP NRW single unit concept fulfils the requirement to balance reliable power supply, sustainable use of existing resources and economic operation.

Assuming a commissioning date before 2010, the design is based on materials and technology that are available today and have proven reliability in use.

Evaluation factors such as improved efficiency, reduced auxiliary power requirement have been determined for the study based on an estimate of medium-term market conditions.

Alternative technical solutions were considered and selected using these evaluation factors, taking account of more extensive evaluations based on the experience of plant operators and manufacturers / vendors. The overall plant concept determined in this way and optimized for technical and economic factors is referred to below as the Preferred Variant.

Design criteria have been drawn up on the basis of evaluation factors derived from a medium term estimate of market conditions. I.e. the following evaluation factors depending on market have been used for the overall plant optimization:

- 17.4 Euro / kW (gross) per %-pt. reduction of plant's auxiliary power,
- 15.5 Euro / kW (gross) per %-pt. increase in plant-net-efficiency.

Features of the RPP NRW - Turbine-Generator set

The used turbine modules belong to the Siemens steam turbine product line named H-I-L with best reliability and availability values over the last decades. This turboset consist of separate HP, IP and LP turbine sections. The turbine will be installed on the turbine floor of the turbine building (+ 16 m) on a spring-supported foundation decoupled from the overall structure.

[4] A table foundation for the turboset would be also possible.

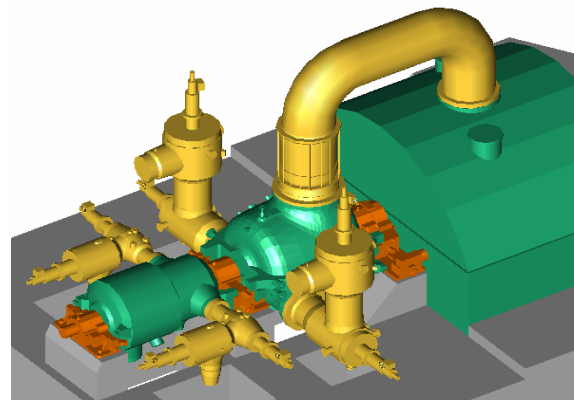


Figure 6: Turboset RPP NRW

To meet the plant performance goals of highest efficiency the parameters for the main steam entering the turbine section are 600°C at 285 bar for life steam and 60 bar 620°C for reheat steam.

To carry this parameters and at the same time to allow a flexible operation (start up/ load changes) the HP cylinder is a barrel-type turbine, equipped with an inner casing. In the inlet flow area of the IP cylinder temperature reduction is achieved by an inherent cooling principle - so-called Vortex cooling. Therefore active steam cooling of the high temperature components in the steam inlet area is not required.

The IP turbine is a double-flow, dual-shell turbine section. The materials for the shaft and inner casing are high-alloy chromium steels. The outer casing is made of nodular cast iron. This IP turbine module is designed for maximum reheat temperatures. As a outstanding reference the power plant “Isogo”, Japan with a reheat temperature of 610°C can be stated. A further increase in reheat temperature to 620°C, affects the creep-rupture strength of the shaft material. The use of a slightly modified alloy content for the 10% chromium shaft material can increase the material strength. The use of 10 % chromium steel with boron shows promising results.

Tests of creep-rupture strength for a shaft-like body are available from a German research project (VGB 158). The results are in alignment with the expected increase of creep rupture strength (time frame > 30,000 hours).

Siemens applies newest HP/IP blade technology called 3DV™ (3-dimensional design with variable reaction). Stage reaction describes the split of pressure drop and velocity increase between fixed and moving blades and is defined by the ratio of the enthalpy drop through the rotating blade row to the enthalpy drop through the whole stage. With 3DV blading the stage reaction and stage loading for each row will be numerically optimized to gain highest HP and IP efficiencies.

The double flow low-pressure turbine is characterized by an exhaust steam area of the final stage of 16 m² per flow.

As result of the very high centrifugal forces acting on the rotor the last stage blades could not be made of steel.

Design Features 16m ² -last stage blade	
• Rotor diameter	~ 1900mm
• Blade length	1400mm (55'')
• Velocity at blade end	750m/s (~ Ma = 2.0)
• Mach-number	Supersonic at blade end
• Blade connection	Shroud & snubber
• Exit losses	3D effects

Figure 7: Last stage blade features

Therefore they will be made of a titanium alloy with higher yield strength.

The profile of the last stage blade has a three-dimensional design with a supporting mid span snubber. Tip clearance losses of the blade are reduced by integral shrouding. The mid span snubber and the integral shrouds give excellent damping behavior of the complete assembled stage.

A Siemens design feature to minimize the axial clearances in the LP turbine blade-path is a rigid connection via push rods which are implemented between the intermediate-pressure outer casing and the low-pressure inner casing. This push rod concept for the H-I-L series turbine allows thermal axial expansion of the rotor system (moving blades) and that of the casing (stationary blades) to be matched. The result of this is a reduction in the axial clearances for the sealing elements between rotor and casing, and thus an improvement in the efficiency of the turbine-generator.

Features of the RPP NRW - Water steam cycle

The water steam cycle essentially consists of the steam turboset with the single pressure condenser, the 2 x 100 % main condensate pumps, the low-pressure (LP) preheating line, the feedwater tank, the 3 x 50 % electric driven feedwater pumps with variable speed control and planetary gearing, the high-pressure (HP) preheating line with 8-stages with external desuperheater and the BENSON² type supercritical steam generator.

² BENSON is a Siemens Trademark

Important characteristics are:

- Frequency control through condensate throttling
- Condensate cleaning in the by-pass (separate 1 x 100 % condensate cleaning pump)
- 8 stage preheating concept with external desuperheater
- 100 % high-pressure by-pass station with safety function
- 60 % low-pressure by-pass station

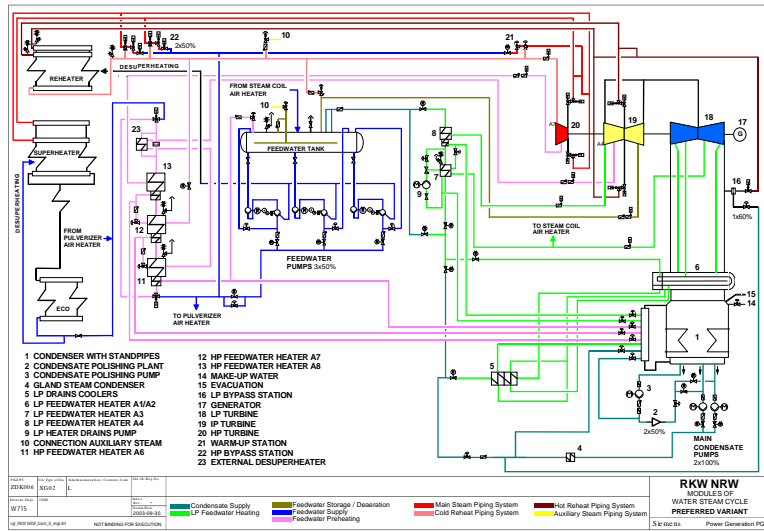


Figure 8: RPP NRW Water Steam Cycle

Features of the RPP NRW - Others

The RPP NRW is developed for an inland location and considers therefore a natural-draft wet cooling tower.

The natural-draft wet cooling tower operates on the counter flow principle and features an inlet line for admission of clean flue gas from the flue-gas desulphurization system. The cooling water heated in the condenser, is distributed on to the packing by the cooling-tower hot water distribution system and spray nozzles. The water is cooled through contact with the air flowing through the cooling tower. The clean flue gas is admitted to the cooling tower via a central inlet.

Features of the RPP NRW – Overview

The main features of the Preferred Variant of the RPP NRW are:

Gross capacity:	600 MW
Type of boiler:	Tower-type boiler with vertical tubes and steam coil air heater
Heat recovery:	Utilization of mill air heat recuperation
Flue gas discharge:	Discharge via cooling tower
Turbine model:	H60 / I60 / L2 x 16 m ²
Main steam parameters:	285 bar / 600°C / 620°C @ turbine inlet
Condenser pressure:	45 mbar
Generator:	Water/hydrogen cooling
Feed water heating stages:	8 feed water heaters + external desuperheater
Feed water final temperature:	303.4°C
Feed water pump concept:	3 x 50 % electric motor-driven feed water pumps, variable-speed drive with planetary gearing

Optimized Economic Efficiency

The evaluation factors applied reflect the market conditions anticipated for the operating life-time of the reference power plant. The plant concept achieves a net efficiency of 45.9 %, based on an outdoor temperature of 11 °C, the use of coal with 25 MJ/kg (LHV), 45 mbar condenser pressure and refers to the energy input and net power output at the generator transformer high-voltage terminal. This includes the auxiliary power necessary for the operation of the plant.

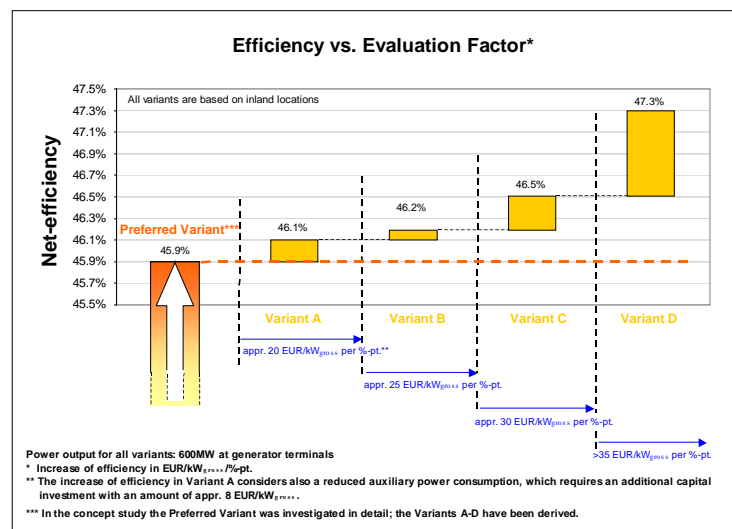


Figure 9: Steps of efficiency increase vs. required evaluation factors

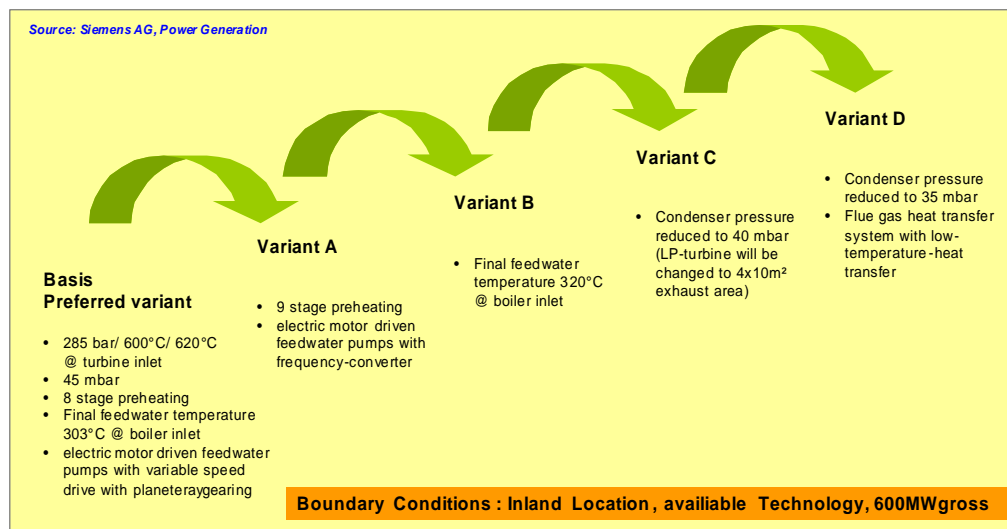
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Technical solutions with higher specific investments will be applied if the market boundary conditions will lead to higher evaluation factors. In a marginal case the specific additional investments may be exactly as high as the "evaluation factor". If the investment is higher, the economic feasibility of the entire project would be reduced but, if the investment is lower the project's internal rate of return will increase.

If it is decided to build the power plant on a costal site and to use fresh water cooling the condenser pressure can be reduced to 25 mbar with a corresponding increase in efficiency. In addition, this site advantage would reduce the cost of investment compared to the Preferred Variant. A comparison between the Preferred Variant and a power plant with the option of fresh water cooling shows an improvement in efficiency of around one percentage point up to 47%, thanks to the higher cycle efficiency and the lower auxiliary power requirement.

Measures for further efficiency increase

Based on the Preferred Variant further steps of efficiency increase with special focus on the water steam cycle were investigated. Assuming that the economic evaluation factors are higher than in the Preferred Variant, as a result of changing boundary conditions (e.g. CO₂ emission costs), the enhancement options summarized in Figure 9 could then be of interest. In this context, the Preferred Variant with all its boundary conditions would be the basis for Variant A. Variant A, in turn, would be the basis for Variant B, etc. Details are shown in Figure 10.



Turbine drive boiler feedwater pumps were not investigated, due the fact that the increase of efficiency in comparison to feedwater pumps with frequency-converters is marginal and the capital cost are much higher than the advantage.

Figure 10: Steps of efficiency increase

Based on the Preferred Variant (steam parameters: 285 bar / 600°C / 620°C), an increase in the main steam parameters to 300 bar / 630°C / 630°C is possible. The planned steam turbine system then features a H-I-L series turbine with active steam cooling in the HP and IP sections. However, it must be pointed out at this point that the increased main steam and reheat temperatures entail a higher operating risk for the main steam/reheat lines and the boiler heating surfaces. At these elevated temperatures, the material planned to be used (P92, E911) has a tendency to internal scaling, which will require additional action after the plant has been operated for a certain time. In addition, the current state of the art does not as yet permit fabrication of major components such as headers and connecting lines that can accommodate the above steam conditions from these materials. In addition, the welds do not feature the required creep strength for long-term service under such conditions. As a result,

for reliable implementation in an economically viable plant with main steam parameters of 300 bar / 630°C / 630°C, which would yield efficiency rates of over 48 %, considerable research is still required.

Activities at the other markets

The current development on Asian power plant market with special focus on China shows high steam parameter of 250 bar - 280 bar / 600°C / 600°C at a power output up to 1100 MW. The design solution for these steam parameter requirements is a Siemens four turbine cylinder turboset (Figure 2) with proven and optimized design features and proper material choice as described above.

Beyond the current steam parameter on the Chinese market an increase of the reheat temperature at maximum power output to 620°C is feasible. This increase of hot reheat temperature of 20 K results in an increase of thermal efficiency of about 0.5 % . Looking onto the need for operational flexibility which is also a more and more important requirement of power plant owners the answer is a throttle controlled full-arc steam admission to HP- and IP-turbine. Together with a boiler operating in slide-pressure mode this gives the best solution concerning highest efficiency for part and full load operation. Fast load changes, e.g. for additional power control, can be achieved by a so called overload inlet at the HP turbine. With this by-pass for live steam to the turbine extra mass flow of up to 10 % can be gained. This extra load can be added onto the stationary operation of the turboset. Therefore a nozzle control design with partial arc admission can be made obsolete.

Future perspective for advanced steam parameter

The current R&D activities include work packages for 350 bar / 700°C steam turbine materials for future application. The chance for a successful design is seen by using the class of superalloys in the steam turbine. These leads to much stronger restrictions in size and difficulties in material behavior compared with known steam turbine materials, as it was the case as the new 10 Cr steels were developed and introduced. The superalloys with their physical properties can better fulfill the required behavior and have at the same time a higher creep strength than austenites. Material and component tests respectively will be started in a existing plant in Germany this year. First results are expected with the beginning of 2007. The EU R&D project “Advanced 700°C Pulverized Fuel Power Plant (AD700)” especially has enabled a continuous development of this 700°C technology. The goal of AD700 is the creation of a 700°C demonstration power plant and the introduction of this technology on to

the market by 2014. Structured in Boiler Group, Turbine Group and Process Group, development work has been done for the corresponding critical components as well as for general topics.

Conclusion

Requests for the near future at the European market – main steam parameters vs. operation flexibility

With the Reference Power Plant NRW a power plant concept was developed with a focus on base load operation, high efficiency due to highest steam parameter and reliable materials. In addition an option package for high flexibility was also considered. With the given partial HP-bypass³ included in the flexibility package of the RPP NRW allows for unrestricted operation a peak load capability.

The study RPP NRW based on the utilization of existing and proven materials in combination with the highest current available main steam parameters. All technological feasible efficiency measurements were investigated and evaluated with economic evaluation factors which reflect the market conditions. The outcome is an economical competitive power plant with an advanced steam turbine and water-steam-cycle technology resulting in a net-efficiency of 46 %.

Today one year after the concept study Reference Power Plant North Rhine-Westphalia operational flexibility and larger unit sizes become more and more important. The market trend is to operate coal fired power plants not only at base load conditions but also in the intermediate load range combined with high load ramps.

These requirements are in the focus of the current Siemens development activities. An optimum between efficiency requirements and operational flexibility needs to be found. The basis of all these investigations is the Reference Power Plant North Rhine-Westphalia. The optimum depends on the evaluation scale of each utility, which depends on political boundary conditions, electricity market structure and availability of resources.

³ Siemens Patent pending

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