Feature Article

# Malaysia's Entry to Ultra Supercritical Boiler Technology Club**

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## INTRODUCTION

This write-up will be of interest to our steam engineers working in all palm oil mills in Malaysia as well as in Indonesia. Perhaps this will inspire the mill owners to consider improving their current dated technology they are holding tight to high-tech boiler technology for their mill boilers. This technology is not new as it is a common knowledge for mechanical engineers that at high superheat temperatures the specific steam consumption will be low resulting in high boiler efficiency. At high boiler pressures and the corresponding steam temperatures, the boiler tubes will have to be made of costly alloy steel as the normal steel has its limitations to withstand the high gas temperatures prevailing in the boiler furnace. This is equally true for high altitude jet propelled fighter aircraft gas turbines whose ability to withstand the gas temperature of the hot gases determines its performance during combat operations.

For those who are not familiar with the super critical pressure, the best way to understand it is to look at the temperature-entropy diagram for steam. The steam flow will not cross the diagram but will move upwards towards the critical pressure point above the bell shaped curve; the water and steam becoming a homogenous mixture with no wet region as you would expect when crossing the temperature-entropy curve below its apex.

Malaysia can be proud to be the only country in South-east Asia to own a high technology-based thermal power station by October 2017. The United States, Europe and some countries like Japan, India and China have a number of them in operation. It is quite sensible that most of the new power stations built around the world are now adopting the ultra super critical pressure boilers for their power plants. The thermodynamic possibility of such a technology is not something new to the mechanical engineers as a simple sketch of the temperature entropy curve indicating the path of the steam flow when its pressure and temperature is raised at the supercritical region would indicate that the steam does not have to go through the

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Note: ** *Some parts of the articles were extracted from newspaper reports and Wikipedia.*

wet region to pick up the latent heat. Now the technology can be translated into actual power plant as boiler tubes made of special alloy steel that can withstand high furnace gas temperatures are within the reach of most of the developing nations.

The palm oil mills can also join the bandwagon as any boiler using fossil fuel or biomass can be catapulted to the supercritical pressure regions by modifying the boilers. The can happen only if there is a paradigm shift by the local boiler manufacturers by changing their focus from one that caters for the processing requirement to one that focuses on power generation as the main thrust. This reasons are not difficult to comprehend.

## THE BOILER MAKER'S CHOICE – HIGH TECHNOLOGY OR LOW TECHNOLOGY

The boiler makers need to wake up to the realities of what the mills will need in the near future. Currently, everything looks bright as the boiler sales are good and profit margin is attractive. If mills can make more profit by selling the electricity than palm oil, the shift to fuel efficient boilers can be expected any time now. The sugar industry, as we are aware, makes more profit out of power production than the sale of sugar itself. But we need efficient boilers to cater for power plants. The specific steam consumption for power generation in a palm oil mill is very high and it is not sensible to consider power generation with such a high steam consumption of 25 kg per kWhr. The local boiler manufacturers should consider modifying their boilers for producing high pressure steam at high superheat temperature, preferably supercritical temperatures.

None of the boiler manufacturer's in Malaysia appear to be ready to cater for our present boiler requirement or even future requirement. In order to express it in simple language, we are not producing steam at the right pressure and temperature for us to venture into serious power production. If we get only 1 MW now from the available steam, we can double or triple it by superheating the same steam. For that we need high pressure boilers that may cost more due to the need for special alloys for making the boiler tubes. If we do not go for high technology boilers, we may not make much progress in power generation. The boiler makers must make the right move if they want to remain competitive.

## THE PRESENT MILL SET-UP *vs.* THE FUTURE NEEDS

The present power generation is based on the concept of generating steam at 20 barg or 30 barg and admitting this in the steam turbine where it expands to 3 barg pressure (performing a Rankine cycle). It uses about 25 kg steam to generate 1 kWhr energy. However, some manufacturers claim that the specific steam consumption of their turbines is 17 kg. In this case, the saturated steam temperature at 20 barg is 214.7°C. If this is superheated to 500°C, the specific steam consumption can be reduced considerably. By superheating the steam, it may be possible to generate 4 MW power from a 60 t $hr^{-1}$ mill. We can design many configurations and after calculations can opt for the most suitable one. One such configuration (not necessarily the best choice) is shown below:

Basic requirement to be satisfied in production of process steam: 60 x 0.6 = 36 t $hr^{-1}$

Boiler pressure 65 barg, 60 t $hr^{-1}$ superheated steam at 550°C (280°C super heat). (i) High pressure multi-stage non-condensing turbine with steam flow rate of 60 t $hr^{-1}$ at 65 bar, exhaust at 30 bar followed by reheating 30 t $hr^{-1}$ steam to 45 bar and admit in (ii) intermediate pressure multi-stage condensing turbine exhausting at 0.5 bar, (iii) the remaining 30 t $hr^{-1}$ steam: admit in a non-condensing turbine and exhaust at 3 bar for process heating. The bleed off steam also can be used for process heating. Final condensate to be 30 t $hr^{-1}$. The process flow is shown in *Figure 1.* The configuration given in *Figure 1* is only an example. A number of thermodynamic calculations have to be conducted before confirming that it can give the desired output.

During the expansion in the multi-stage condensing turbine, the bleed-off steam can be used for process heating. It may also be possible to go to high boiler pressures (say 65 bar) and reheat the steam after its expansion in the high pressure turbine to intermediate pressure followed by medium pressure multi-stage turbine at 40 barg exhausting at 0.5 barg.

Probably, we should modify our existing power station by replacing the existing boilers with high pressure boilers and turbines. The power station to be located at Manjung in Perak will have high technology boilers generating steam at high ultra critical pressure and superheat so that the thermal efficiency of the power plant will be close to 46% almost double that of the conventional boilers.

## MALAYSIA'S FIRST HIGH TECHNOLOGY POWER PLANT

The new power plant is being constructed next to the existing power plant, in Perak, 10 km south of the nearest town Lumut, approximately 288 km north of Kuala Lumpur and close to the tourist island of Pangkor. It will be the first coal-fired power plant in Malaysia using supercritical technology and the single largest unit in South-east Asia. The estimated cost of the whole project is RM 5.5 billion (1 billion Euro). This is a sensible move by TNB as the same amount of fuel will be capable of generating double the power output.

## CONTRACTOR CONSORTIUM

The contract for engineering, procurement and construction (EPC) has already been signed by TNB-owned Western Energy Bhd (TWE) with a consortium of four companies to develop a 1000 MW coal-fired power plant in Perak. The consortium com-

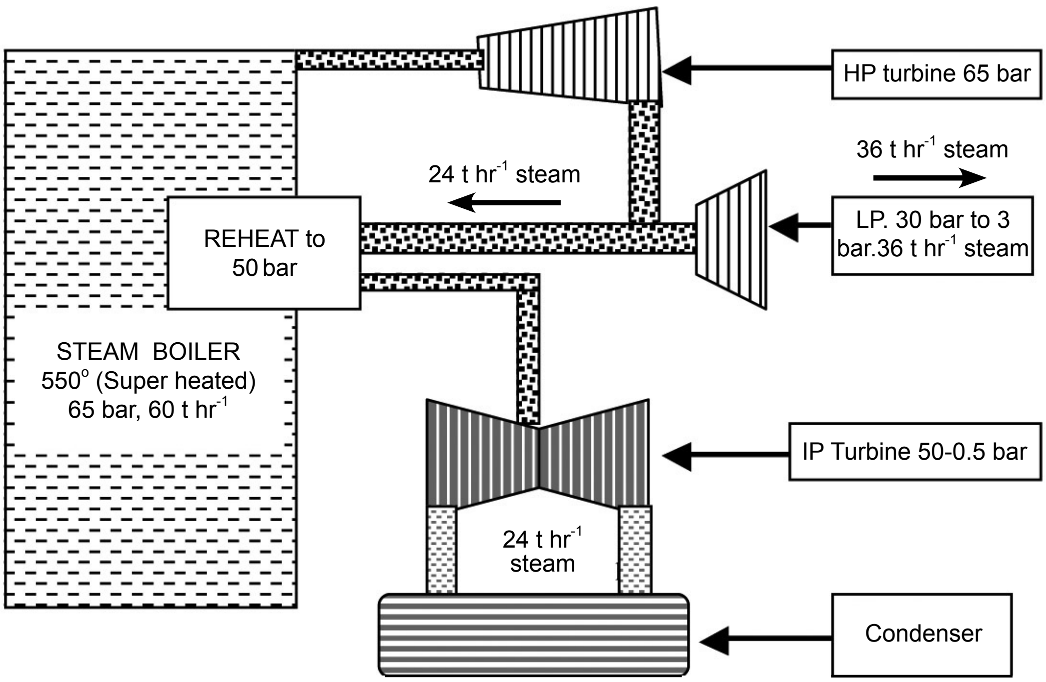


*Figure 1. An example of a power plant cum process heating configuration.*

prised Sumitomo Corporation, Daelim Industrial Co. Ltd, Sumi-Power Malaysia Sdn Bhd and Daelim Malaysia Sdn Bhd. TWE is a unit of TNB Manjung Five Sdn Bhd, a wholly-owned subsidiary of TNB.

The consortium will be responsible for the design, supply, construction and commissioning of the coal-fired thermal powers station that is targeted to be in operation by 1 October 2017. The new power plant will utilise the ultra supercritical boiler technology that is more efficient than current conventional boilers operating in Malaysia. The ultra supercritical boiler technology will also reduce the carbon dioxide emissions.

Astrom and its consortium partners have signed the contract for RM 3.575 billion with TNB's Janamanjung Sdn Bhd. Astom's share in this contract amounts to €830 million.

The plant is expected to be online in 2015 providing an extra 1000 MW of power to the Malaysian grid. This power plant is reported to be Astrom's second project in Malaysia following TNB's 1999 contract with them to build the 2100 MW Manjung coal-fired power station comprising three 700 MW turbo alternator units, which came into operation in 2004.

The emissions at the plant will be significantly reduced through the use of low NOx burners, a highly efficient seawater flue gas sulphur removal facility and fabric filters to lower nitrous oxide, sulphur oxide and dust emissions. Additionally, Alstom will also supply and install its latest ALSPA® Series 6 Distributed Control System.

## FEATURES

Up to an operating pressure of around 190 bar (2755 psig) in the evaporator part of the boiler, the cycle is subcritical. This means, that there is a non-homogeneous mixture of water and steam in the evaporator part of the boiler. In this case, a drum-type boiler is used because the steam needs to be separated from water in the drum of the boiler before it is superheated and led into the turbine. Above an operating pressure of 221 bar (3205 psig) in the evaporator part of the boiler, the cycle is supercritical. The cycle medium is a single-phase fluid with homogeneous properties and there is no need to separate steam from water in a drum. Once-through boilers are therefore used in supercritical cycles.

## SUPERCRITICAL STEAM PRESSURE

The power plants with supercritical pressures are designed to operate at about 300 bar and 600°C capable of operating with 46% efficiency compared to 23% for superheated steam operating at below 450°C. In addition, they have lower emissions than the subcritical power plants. The other advantages are:

- reduced fuel costs due to improved plant efficiency;
- significant reduction in $CO_2$ emissions;
- excellent availability, comparable with that of an existing subcritical plant;
- plant costs comparable with subcritical technology and less than other clean coal technologies;
- much reduced NOx, SOx and particulate emissions;
- compatible with biomass co-firing;
- can be fully integrated with appropriate $CO_2$ capture technology; and
- in summary, highly efficient plants with best available pollution control technology will reduce existing pollution levels by burning less coal per megawatt-hour produced, capturing the vast majority of the pollutants, while allowing additional capacity to be added in a timely manner.

## PROJECT FEATURES

The Manjung 4 Project will have the following high technical components:

- one two-pass, ultra-supercritical, once-through PC boiler (tangential firing low NOx combustion system);
- one STF100 steam turbine with one high-pressure, one intermediate-pressure;
- two double-flow low pressure turbines for high efficiency and reliability;
- one two-pole GIGATOP turbo-generator with the most advanced water/hydrogen-cooling technology for generators, providing high efficiency, outstanding reliability and simple maintenance;
- Alstom's latest ALSPA® Series 6 Distributed Control System;
- environmental control systems (seawater flue gas desulphurisation and pulse jet fabric filter) to reduce flue gas emissions;
- the Manjung 4 ultra supercritical, higher steam parameters will result in a reduction in operational costs;
- fourteen percent more power generated per tonne of coal burned, compared to the existing Manjung wide range of coal quality Manjung 4 unique TSF 2000 firing system enables to burn a wide range of coal, either bituminous and sub-bituminous >90% $SO_2$ removal;
- Manjung 4 benefits from the seawater flue gas desulphurisation system, designed to treat the complete flue gas;
- reducing cost of electricity, increasing flexibility and reliability lowering environmental footprints; and
- particulate emissions: more than 99% of particulate dust is removed via an electrostatic precipitator (ESP).

## ALLOY STEELS

Currently, for once-through boilers, operating pressures up to 300 bar (4350) represent the state-of-the-art. However, advanced steel types must be used for components such as the boiler and the live steam and hot reheat steam piping that are in direct contact with steam under elevated conditions. Therefore, a techno-economic evaluation is the basis for the selection of the appropriate cycle parameters. *Figure 2* depicts the schematic diagram of a pressure power plant.

## STEAM CONDITIONS

Most nations are now considering the installation of ultra supercritical pressure boilers in their new power stations to improve their power generation efficiency. Today's state-of-the-art in supercritical coal fired power plants permit efficiencies that approaches even 50% that is more than double that of yester-years. This means the fuel currently used for power generation can produce double the output using the new technology. Options to increase the efficiency above 50% in ultra supercritical power plants rely on elevated steam conditions as well as on improved process and component quality.

Steam conditions up to 300 bar (4350 psig)/600°C/620°C are achieved using steels with 12% chromium content. Up to 315 bar/620°C/620°C is achieved using austenite, which is a proven, but expensive material. Nickel-based alloys, *e.g.* inconel, would permit 350 bar/700°C/720°C, yielding efficiencies up to 48%. Manufacturers and operators are cooperating in publicly sponsored R&D projects with the aim of constructing a demonstration power plant of this type.

Other improvements in the steam cycle and components can yield a further 3% points rise in efficiency. Most of these technologies, like the double re-heat concept where the steam expanding through the steam turbine is fed back to the boiler and re-heated for a second time as well as heat extraction from flue gases have already been demonstrated. However, these technologies are not in widespread use due to their cost.

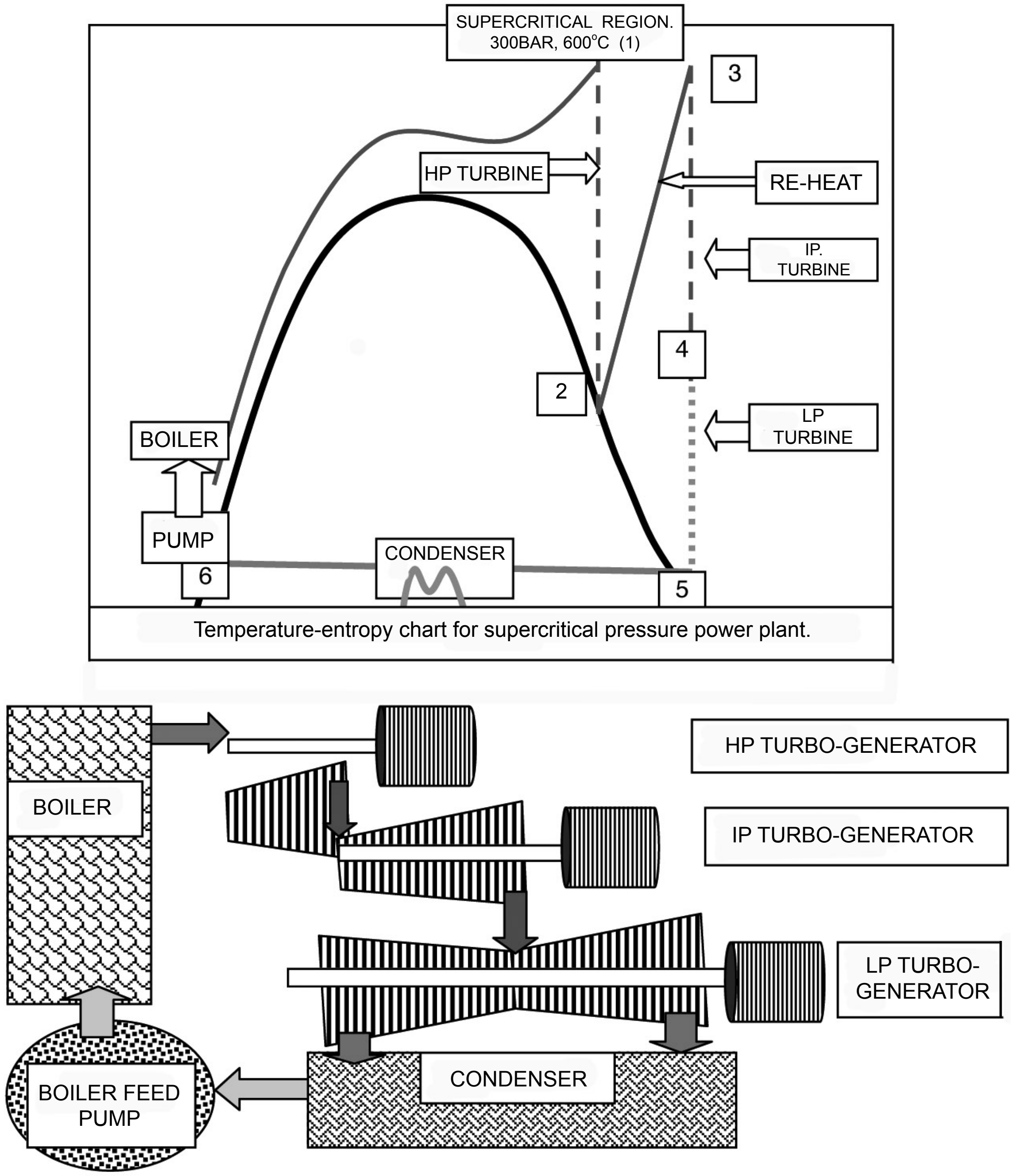


*Figure 2. Schematic diagram of the supercritical pressure power plant.*

## THE TEMPERATURE-ENTROPY DIAGRAM

The most exciting part of the ultra supercritical boiler is the diagram that shows how the steam pressure line circumvent the bell curve and settle at the top without crossing the wet steam region. This is done by pressurising the feed water that causes a gradual rise of pressure to 351 bar followed by constant pressure heating in the boiler to attain a temperature of 700°C. If this steam is subjected to isentropic expansion in a steam turbine, the Rankine cycle will cross the temperature-entropy curve in the middle, which being a very wet area will cause considerable damage to the turbine blades. Perhaps a few re-heat stages will enable the low pressure end of isentropic expansion line to settle close to the steam saturation curve. The intermediate pressures can be at 70 bar.

## TURBINE GENERATOR SET

There are several turbine designs available for use in supercritical power plants. These designs need not fundamentally differ from designs used in subcritical power plants. However, due to the fact that the steam pressure and temperature are more elevated in supercritical plants, the wall-thickness and the materials selected for the high-pressure turbine section need reconsideration. Furthermore, the design of the turbine generator set must allow flexibility in operation. While subcritical power plants using drum-type boilers are limited in their load change rate due to the boiler drum (a component requiring a very high wall thickness), supercritical power plants using once-through boilers can achieve quick load changes when the turbine is of suitable design.

### High-pressure Turbine (HPT)

In this section, the steam is expanded from the live steam pressure to the pressure of the re-heat system, which is usually in the order of 40 bar to 60 bar. In order to cater for the higher steam parameters in supercritical cycles, materials with elevated chromium content, which yield higher material strength, are selected. The wall thickness of the HP turbine section should be as low as possible and should avoid massive material accumulation (*e.g.* of oxides) in order to increase the thermal flexibility and fast load changes.

### Intermediate-pressure Turbine (IPT)

The steam flow is further expanded in the IPT section. In supercritical cycles, there is a trend to increase the temperature of the re-heat steam that enters the IPT section in order to raise the cycle efficiency. As long as the re-heat temperature is kept at a moderate level (approximately 560°C), there is no significant difference between the IPT section of a supercritical plant and that of a subcritical plant.

### Low-pressure Turbine (LPT)

In the LPT section, the steam is expanded down to the condenser pressure. The LPT sections in supercritical plants are not different from those in subcritical plants.

## ONCE-THROUGH BOILER

Apart from the turbine generator set, the boiler is a key component in modern, coal-fired power plants. Its concept, design and integration into the overall plant considerably influence costs, operating behaviour and availability of the power plant.

Once-through boilers have been favoured in many countries, for more than 30 years. They can be used up to a pressure of more than 300 bar without any change in the process engineering. Wall thicknesses of the tubes and headers are designed to match the planned pressure level. At the same time, the drum of the normal water tube boiler, which is very heavy and located on the top of the boiler, can be eliminated. Since once-through boilers can be operated at any steam pressure, variable pressure operation was introduced into power plants at the start of the 1930s to make the operation of plants easier.

Once-through boilers have been designed in both two-pass and tower type design, depending on the fuel requirements and the manufacturers general practice. For the past 30 years, large once-through boilers have been built with a spiral shaped arrangement of the tubes in the evaporator zone. The latest designs of once-through boilers use a vertical tube arrangement.

## OTHER CYCLE COMPONENTS

A comparison of the water-steam cycle equipment in subcritical and supercritical coal fired power plants shows that the differences are limited to a relatively small number of components, *i.e.* to the feed water pumps and the equipment in the high-pressure feed water train, *i.e.* downstream of the feed water pumps. These components represent less than 6% of the total value of a coal-fired power plant.

## HIGH EFFICIENCY AND MORE RELIABILITY

### Operational Issues

More than 400 supercritical power plants are operating in the US, Europe, Japan, China and India. Availability of supercritical plants is equal or even higher than those of comparable subcritical plants. There are no operational limitations due to once-through boilers compared to drum type boilers. In fact, once-through boilers are better suited to frequent load variations than drum type boilers, since the drum is a component with a high wall thickness, requiring controlled heating. This limits the load change rate to 3% per minute, while once-through boilers can step-up the load by 5% per minute. This makes once-through boilers more suitable for fast start-up as well as for transient conditions.

### Fuel Flexibility is not Compromised in Once-through Boilers

All the various types of firing systems (front, opposed, tangential, corner, four wall, arch firing with slag tap or dry ash removal, fluidised bed) used to fire a wide variety of fuels have already been implemented for once-through boilers. All types of coal as well as oil and gas have been used. The pressure in the feed water system does not have any influence on the slagging behaviour as long as steam temperatures are kept at a similar level to that of conventional drum type boilers.

### Life Cycle Costs of Supercritical Coal Fired Power Plants

Current designs of supercritical plants have installation costs that are only 2% higher than those of subcritical plants. Fuel costs are considerably lower due to the increased efficiency and operating costs are at the same level as subcritical plants. Specific installation cost, *i.e.* the cost per megaWatt decreases with increased plant size. Some of the latest installations in China that had been making headlines recently are given below:

***Yuhuan 1000 MW ultra supercritical pressure boilers, China.*** All four 1000 MW coal-fired ultra supercritical pressure boilers at Yuhuan in China have come online. Located on the coast of east China's Zhejiang Province, the last unit began commercial operation in November 2007. The plant cost ¥ 9.6bn (€ 900m), and the units run at about 45% efficiency. Yuhuan has China's first 1000 MW ultra supercritical pressure boilers. Units 1 and 2 went online in 2006, and Units 3 and 4 in 2007. The site is now generating 22 billion kWhr of electricity a year. The plant is operated by China Huaneng Group, China's largest power producer. It is claimed that Yuhuan Units 1 and 2 are the world's cleanest, most efficient and most

advanced ultra supercritical units. When Unit 4 is working, the site will generate 22 billion kWhr of electricity a year.

***Ultra supercritical pressure boilers.*** Supercritical operation of large thermal baseload power plants during the 1980s used steam temperatures of typically 550ºC, leading to around 40% thermal efficiencies. Ultrasupercritical steam conditions now use supercritical pressures up to 300 bar, with 600°C steam and re-heat steam temperatures. This gives a net efficiency of 46%.

Siemens reports that just a 1% gain in efficiency for a typical 700 MW plant reduces 30-year lifetime emissions by 2000 t NOx, 2000 t $SO_2$, 500 t particulates and 2.5 million tonnes $CO_2$.

New units also incorporate high efficiency dust removal and desulphurisation. This has led to the claim that Yuhuan Units 1 and 2 are the world's cleanest, most efficient and most advanced ultra supercritical units.

The MHI boilers have a main steam pressure of 27.5 MPa, a main steam temperature of 605°C and a re-heat steam temperature of 603°C. The boilers were made and commissioned collaboratively by MHI in Japan, which provided the designs and key products, and Harbin Boiler Co. (HBC) in China. Unit 4 was constructed by MHI and HBC. MHI plans to supply above 12 GW of boilers to China under the HBC collaboration.

Siemens is supplying four 1000 MW ultra supercritical steam turbines. These use a tandem compound, four-cylinder arrangement. Steam enters the high-pressure turbine through two main steam valves, with exhaust steam being re-heated and fed to a double-flow intermediate-pressure turbine. From there, it goes to two low-pressure turbines. The steam turbines at the Yuhuan power plant were jointly designed and manufactured by Shanghai Electric Group and Siemens Power Generation Group.