Supercritical and Ultra-Supercritical Power Plants – SEA's Vision or Reality?

Miro R. Susta, IMTE Switzerland & Khoo Boo Seong, Zelan Malaysia

www.powergolflink.com

INTRODUCTION

Power plants using conventional fossil fuels supply more than 70% of the total world's electricity production. The demand for energy is closely related to economic growth and standard of living. Currently, demand for all global energy is increasing at an average rate of approximately 2% per annum. This rate is expected to continue.

Forecast of a substantial rise in natural gas (NG) prices within a short outlook of few years as well as increased worldwide tendency to use oil for other purposes than burning it in power generation plants, causes coal to enjoy its resurgence once again. In other words this means that fuel cost will increase in NG based power plants in comparison to coal based power generation options (Figure 1).

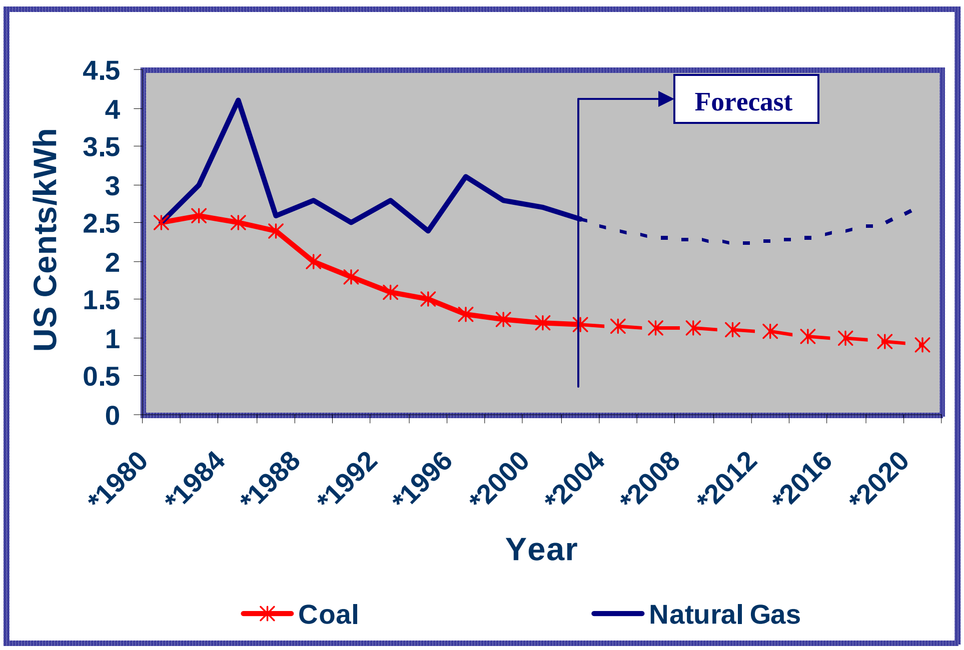


FIGURE 1
FUEL COST FOR COAL AND NG BASED POWER PLANTS BY IEA OUTLOOK

In the 21st century, the world faces critical challenge of providing abundant, cheap electricity to meet the needs of growing global population while at the same time preserving environmental values. The use of coal for power generation poses a unique set of challenges.

On one hand coal is plentiful and available at low costs in much of the world, notably in Asia-Pacific region with more than 30% proven global coal reserves. Coal has played a pivotal role in the industrial development of many Asian countries and is likely to continue to do so. Asian countries with large coal reserves will want to develop them to foster economic growth and energy security.

On the other hand, traditional methods of coal combustion emit pollutants and CO_2 at high levels comparing to other power generation options - the coal fueled power generation is expected to face new challenges. Maintaining coal as a generation option in 21st century will require methods for addressing these environmental issues. The need of further reduction of environmental emissions from coal combustion is driving growing interest in high-efficiency; low-emissions coal fired power plants.

A minor portion of reduction of Green House Gases (GHG) from coal use may be achieved through options like CO_2 trading or credits for investing in emissions reduction projects.

However, substantial reduction in emissions from coal based power plants can be achieved only by employing most advanced and highly efficient modern power generation technologies.

The most direct and economical route to this target is the evolutionary advance of increasing steam temperatures and pressures at the steam turbine inlet well beyond the critical point of water.

To allow these increases, advanced materials are needed that are able to withstand the higher temperatures and pressures in terms of strength, creep, and oxidation resistance.

Due to low economic growth in the past, conventional (sub-critical) steam cycles using pulverized coal combustion are currently in rather limited use for power generation in South-Southeast-East Asia, one of the world's most emerging regions with considerable coal reserves (further called as SEA Region). In recent years the economic growth substantially accelerated in SEA Region and it is expected to exceed 5 to 10 % per year over the period up to year 2010. Electricity demand will rise significantly to meet overall economic growth of this region and the pulverized coal combustion technology will be used more extensively to satisfy all power requirements.

Sub-critical steam cycle is still expected to remain the main choice in some countries of this region due to its simplicity, believe in higher reliability, cost and low technical risk.

However, the need for higher efficiency, lower generation costs and lower emissions would also open opportunities for some application of supercritical (SC) and ultra-supercritical (USC) steam cycles.

It is obvious that the SC & USC coal fired power plant technology is one of the major options for high-efficiency, low-emissions power generation.

Based on significantly higher steam temperatures and pressures beyond those traditionally employed for conventional technology, the operating conditions of SC & USC units put new requirements on steam turbine (ST) and boiler design, particularly where the operational mode demands flexible, reliable cycling operation of power plant equipment.

Motivated by the urgent needs for state-of-art coal fired power generation technologies, SC & USC technologies are undertaken worldwide, mainly in USA, South Africa, Euroasia some other Asian countries and in Europe.

USC power plants have been under development for some time in Japan; more recently, they have become a focus of development work in Europe, with increasing interest among the USA power industry as well.

USC power plants pose particular challenges for maintaining equipment reliability and flexible operation at more-advanced live steam conditions.

Dramatic improvements in materials technology for boilers and ST^s since the early 1980s, plus improved understanding of power plant water chemistry, have led to increasing numbers of new fossil power plants around the world that already employ SC steam cycles.

Many site-specific factors come into play in the selection of a SC technology versus a conventional, sub-critical cycle, including the configured cycles' comparative expected reliability and availability.

The reliability and availability of more recent SC power plants have matched or exceeded conventional units in base load operation, after early problems in first- and second-generation SC boilers and ST^s were overcome.

Today, the SC technology is a mature high efficient fossil power generation technique, which is being continuously developed worldwide and it is listed in the category of clean coal power generation technology class.

This is justified due to efficient coal utilization at lover environmental pollution.

The limited number of coal fired power plants built in USA with conventional (sub-critical) cycles in the past 30 years has been mainly a result of relatively low coal costs that eliminated justification for somewhat higher capital costs of higher-efficiency SC plants.

But in some international markets where fuel cost represents a higher fraction of the total cost, higher-efficiency SC cycles result in lower electricity tariff at reduced emissions, compared with conventional power plants.

This is particularly pertinent for an anticipated future in which emissions of CO_2 are constrained, for example, by international agreements.

More than 600 SC&USC power plants (status 2004), with total capacity above 300 GW, are operating or under construction mainly in Europe, South Africa, USA, Japan, China and Russia. Around 170 units have been commissioned in USA, about 100 in Japan, and more than 60 in Europe. The greatest concentration of SC power plants is in Russia and in the former Eastern bloc countries, where more than 240 are in service providing about 40% of all electricity needs in those countries (Figure 2).

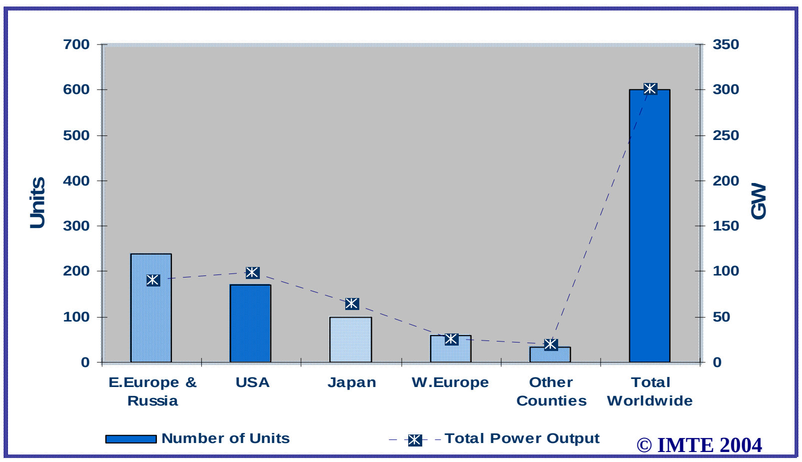


FIGURE 2
CAPACITY OF SC & USC POWER PLANTS WORLDWIDE

Advanced SC designs can now be found at several Asian power plants, with are currently under construction in the People's Republic of China, South Korea and Taiwan with the capacity in range of 25 GW. Emerging interest in advanced SC coal fired power plants has fueled development of new, cutting-edge technologies.

Power plants with record-breaking steam parameters approaching or exceeding levels of 30MPa and 600°C have been commissioned in the last decade or are under construction in Denmark, Germany and Japan.

Strange enough, this is not the case for the traditional developers of SC technology like Russia and the USA. In these two countries no further major growth of SC technology has been seen in the last decade. Most of the 170 US SC power plants with combined installed capacity above 107 GW came on-line prior to 1980. For example the most famous of them, Eddystone 1 that was commissioned in 1960, is still operating with remarkable steam parameters of 32.2MPa and 610°C. It is a fact that more compact SC & USC coal fired power plants with efficiencies in the range of 45% - 50% producing less specific emissions have a great future in the coal fired power generation industry and will replace sub-critical coal based power plants worldwide.

ULTRA-SUPERCRITICAL – DREAM OR REALITY?

Increasing the temperature and pressure in a steam turbine increases the efficiency of the Rankine steam cycle used in power generation, in other words it decreases the amount of fossil fuel consumed and the emissions generated.

An increase in cycle efficiency from 30% to 50% decrease CO_2 emissions by more than 30% as well. Increases in power generating plants efficiencies and decreases in emissions are part of three major USA DOE power generation initiatives: Vision 21, Future-Gen and Clean Coal Power. The Vision 21 initiative has the goal of 7’200[4] kJ/kWh heat rate (η_{th}=50%) for coal fired power plant.

This shall be achieved in two major steps, 675ºC live steam temperature by year 2010 (8’000-7’200 kJ/kWh → η_{th}=45-50% and 760ºC by year 2020 (6’000–7’200 kJ/kWh → η_{th}=50-60%).

The final live steam temperature and pressure goal is 760ºC and 38.5MPa by the year 2020.

Based on high live steam parameters beyond those traditionally employed for SC power plants, the operating conditions of USC units put new demands on ST and boiler design, particularly where the business climate demands flexible, reliable cycling operation of generating units.

A major challenge for USC steam technology is the selection or development of candidate alloys suitable for USC use.

Since the materials for USC boiler (ferritic alloy SAVE12, austenitic alloy Super 304H, the high Cr-high Ni alloy HR6W, and the nickel-base super-alloys Inconel 617, Haynes 230, and Inconel 740) have been already identified, a remaining major challenge is the selection or development of candidate alloys suitable for use in the USC steam turbines.

[4] **Based on HHV**

One of most important aspects is the role of pressure on steam-side oxidation. It is important from that fact that most of the efficiency gains results from ***increased temperature, not pressure***. As a consequence, material requirements, in terms of high temperature strength and steam-side oxidation, could lead to the use of lower pressures (than the goal of 38.5 MPa) to make USC turbines economical, and yet still beneficial in terms of efficiency increases.

Before commercial applications of advanced USC technology, the above has to be investigated in more-or-less time and cost expensive tests.

WHY SUPERCRITICAL AND ULTRA-SUPERCRITICAL?

Historically, it was widely foreseen that from the traditional 18.5 MPa/538°C single reheat cycle, dramatic improvements in coal fired power plant performance could be achieved by raising the live steam pressure to levels above 31MPa and temperatures to levels in excess of 600°C.

For example, using above 18.5MPa/538°C cycle as a base case, an efficiency increase of about 6% can be achieved by changing the live steam conditions to 30MPa/600°C and 8% by changing the steam temperature to 650-720°C.

In 1957, the first USC units were put into commercial operation in UK and USA, the 375MW Drakelow C and the 125MW Philo (610/565/538°C/31MPa) and in 1959 the famous Eddystone 1, which was designed for 650/565/565°C/34.5MPa steam conditions but due to serious mechanical and metallurgical problems it was later down-rated to 605/565/565°C/32.4MPa.

Most of the problems were due to the use of austenitic steels for thick section components operating at high temperatures.

It is well known that austenitic steels have low thermal conductivity and high thermal expansion resulting in high thermal stresses and fatigue cracking.

These problems and initial low availability of many SC power plants temporarily dampened utilities in building SC & USC power plants and consequently most utilities reverted back to power plants with sub-critical live steam conditions of about 550°C/18MPa.

After that, through more than 45 years of practices, fighting with protracted struggles, the technology has been unceasingly developed and gradually perfected.

Operational experience worldwide has brought the evidence, that present availability of SC power plants is equal or even higher than those of comparable conventional (sub-critical) ones.

What is supercritical? It is a thermodynamic expression describing the state of a substance (in our case water/steam) where there is no clear distinction between the liquid and the gaseous phase.

Up to an operating live steam pressure of around 19MPa, the cycle is sub-critical. This means, that there is a non-homogeneous mixture of water and steam in the evaporator part of the boiler.

In this case usually drum-type boilers are used, because the steam needs to be separated from water in the drum, before it is superheated and led into the turbine.

Above an operating live steam pressure of 22.1MPa and temperature of 373°C the cycle is supercritical (Figure 3).

The cycle medium is a single phase fluid (dry steam) with homogeneous properties and there is no need to separate steam from water in a drum.

Once-through (OT) boilers are therefore used in SC cycles.

Additonally to high thermal stresses and fatigue cracking in the boiler sections another notorious reasons why not to build an SC plant were more-or-less related to the higher maintenance costs and lower operational availability and reliability of steam turbines compared to sub-critical units.

Main concerns were related to the ST control valve wear-and-tear, to the turbine blade thermal stress and solid particle erosion problems as well as to more complicated start-up procedures.

SC units are also more sensitive to feedwater quality.

Full-flow condensate polishing, therefore, is required to protect the turbine from stress corrosion cracking.

However, SC units are more efficient and more flexible. Combination of SC design with OT-boiler technology results in better operational dynamics. SC unit ramp rates are higher, namely 7 to 8%/min over a wide output range and in sliding pressure mode compared to about 3-5%/min for sub-critical drum units.

With about 1’000 built units, the Benson Boiler is the most common implementation of the OT design. It can accept a wide range of fire systems, and can be built with essentially the same design for sub-critical and SC steam pressure.

Comparing to sub-critical power plants, SC power plants can maintain higher efficiency at rather low load. On the other hand, conventional drum-type boilers have bigger material requirements because of the thick-wall drums, and also the water/steam inventory.

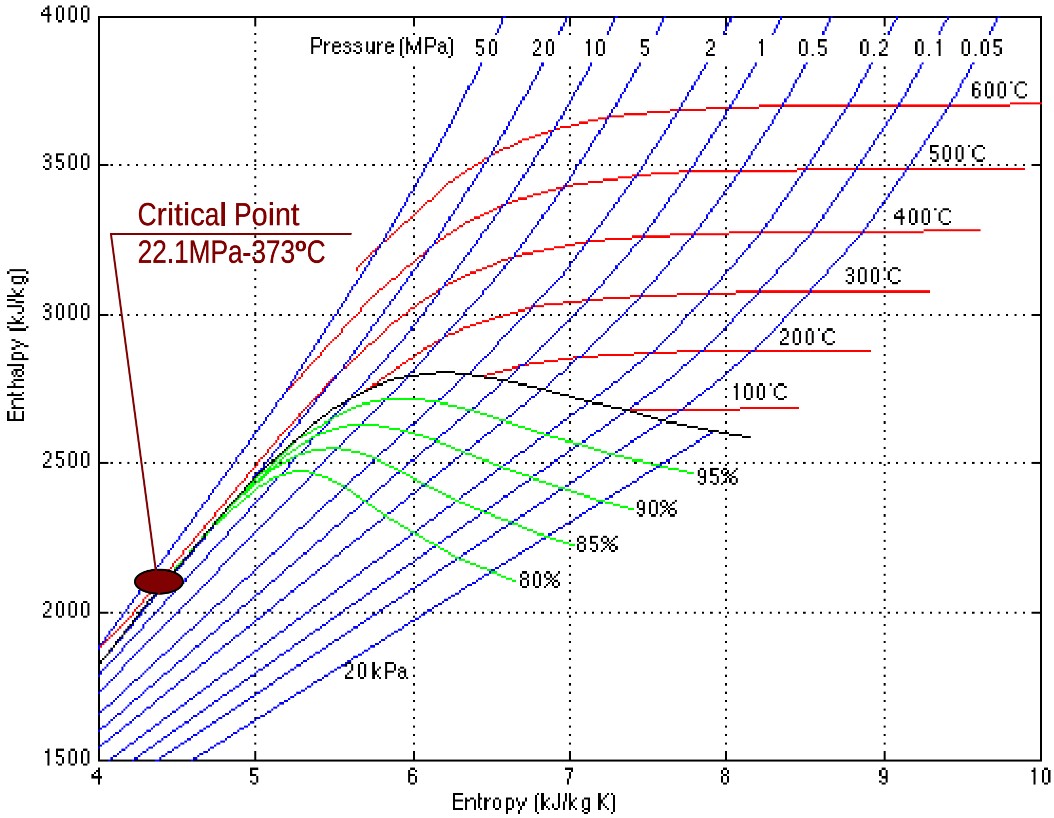


FIGURE 3
H-S DIAGRAM FOR WATER

Fuel prices are taking ever higher economy weight. Markets of the countries, where fuel cost is a higher fraction of the total cost, more efficient SC units offer a more favorable cost-of-electricity comparison and lower emissions than sub-critical units. SC plant reduces carbon emissions comparing to the same size of sub-critical coal unit.

And at last but not least, the expected life cycle costs of SC power plants are lower than those of sub-critical power plants. In the second half of last decade SC technology clearly prevailed over the conventional one in the OECD countries. In this period, more than 20 GWe of new installed SC capacity against merely 3 GWe sub-critical one were installed here.

Various collaborative programs like THERMIE 700 EUROPE, COST 522 EUR, EPRI 1403-50 USA or CRIEPI push the technical envelope of this important clean-coal technology.

In the non-OECD countries, however, the rating for the same period was vice-versa. Only 5% out of new installed capacity was based on SC technology in the second half of last decade.

Table 1 indicates basic data comparison between 580°C/700°C SC/USC and conventional coal fired power plant.

PLANT TYPE	PRICE[5] (US$/kW)	STEAM PRESSURE (MPa)	STEAM TEMPERATURE (°C)	AUXILIARY CONSUMPTION (%)	EFFICIENCY (%)	CO_2 (G/KWH)	SO_2 (G/KWH)
Conventional	850	165	538 / 538	4-6	< 40.0	≈ 855	≈ 2.4
580°C - SC	1050	290	580 / 580 / 580	5-7	> 42.0	≈ 780	≈ 2.2
700°C - USC	1100	365	700 / 700 / 700	6-8	> 48.0	≈ 710	≈ 2.0

TABLE 1
COMPARISON PARAMETERS SC - USC VS. SUB-CRITICAL

Increased live steam pressure to levels above 30MPa leads to higher auxiliary power consumption and to loss of thermal flexibility, comparing to sub-critical systems. The following diagram (Figure 4) illustrates the relative thermal efficiency gain for a variety of steam conditions and boiler material improvement (using Benson type boilers) for single reheat unit compared to the sub-critical 16.7MPa/538°C/538°C cycle.

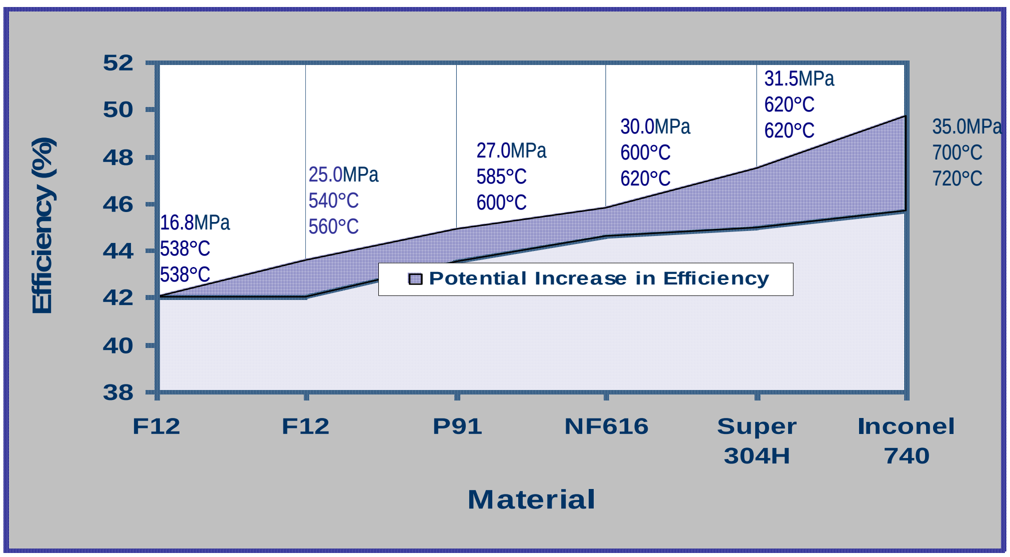


FIGURE 4
POTENTIAL INCREASE IN THERMAL EFFICIENCY

As shown in this diagram, USC cycles with steam temperatures above 700°C, using more expensive nickel based alloys are possible.

Such USC cycles might achieve thermal efficiency of around 48-50% and higher. Limitations on achievable steam parameters are set by creep properties of construction materials for high temperature boiler sections, live steam piping and other components, as well as high temperature corrosion resistance of superheater and reheater materials.

[5] **European Basis**

Higher steam temperatures make the change from ferritic steel to austenitic steel and inconel unavoidable. Conventional technology provides great coal flexibility. Higher temperatures encountered in SC & USC units' makes corrosion problems more critical, thus coals with slugging or corrosion potential are less suitable for SC & USC plants.

MATERIALS FOR USC POWER PLANTS

The major task leading to successful implementation of USC technology is identifying, evaluating, and qualifying potential materials needed for construction of all critical components for boiler and ST, which are capable of operating at much higher efficiencies than current generation of SC power plants.

Efficiency increase is expected to be achieved principally through the use of USC steam parameters by achieving live steam conditions of 760°C and 35MPa. Live steam temperatures of the most advanced and efficient fossil fueled power plants are currently within 600ºC range, representing an increase of about 60ºC within 30 years. Since ferritic steels are capable of meeting the strength requirements up to of approximately 620ºC there is no obstacle for USC technology within this temperature range. It is expected that the live steam temperature will raise another 70–150ºC in next 15-30 years. In order to make this considerable steam temperature increase commercially feasible, the development of stronger high temperature resistant materials capable of operating under high stresses at ever increasing temperatures and pressures plays the most important role.

BOILERS

To satisfy the needs for higher efficiencies and flexible operation, sliding pressure, once-through boilers are most suitable for SC & USC applications.

For high-temperature SC & USC steam conditions, it is essential to use high-strength materials to reduce wall thickness of pressure parts, resulting in low thermal stresses.

High-strength ferritic 9-12 Cr steels for use in boilers are now commercially available up to 620ºC and miscellaneous tests show that they capable of long term service up to 650ºC and possibly 700ºC.

Boiler design technology is currently following the trend of ever higher creep rupture stress materials. Such are steels P91 to P92, austenitic steels 18-8 to 18-25 like Super 304H, Esshete 1250 as well as the high nickel alloys like Inconel 718 and 740 as shown in Figure 4.

The extra costs for nickel based alloys can be partly compensated by reduction in the amount (weight) of material, because of thinner pipe walls and smaller dimensions of machinery.

Also austenitic steel slightly reduces the wall thickness.

Despite of its unfavorable physical properties (thermal coefficient & conductivity) compared to ferritic/martensitic steel, this material is able to follow changing temperatures during accelerated start-up of the turbine.

This is why austenitic steels are used for superheater pipes. Furnace walls need high-temperature creep-resistant feritic steel. T23 & T24 are probable candidates.

Reheat temperature is usually higher (typically by 15-20°C) than main live steam temperature, but because the reheat pressure is typically by 4-times lower than main live steam pressure, lower quality material may be used for reheat systems and components.

SC & USC boiler size reduction may appear to become the decisive factor for even more intensive expansion of SC & USC technology, because this particular problem of extremely high cost of special steels and alloys was traditionally the main obstacle with even wider application of SC & USC technology.

History and outlook of high temperature materials development is shown in Table 3.

LIVE STEAM		WHEN	WHAT
PRESSURE (MPA)	TEMPERATURE (°C)		
<25.0	<520	Since early 60's	X20
<30.0	<593	Since late 80's	P91 (9%Cr)
<33.0	<620	Start 2000	P92 (NF616)
35.0-47.0	700-720	Start 2010	Super Alloys

TABLE 3

COAL FIRED POWER GENERATION-BOILER TEMPERATURE & MATERIAL DEVELOPMENT

As already said, the choice of material for miscellaneous boiler components is a very important factor in application of SC & USC technology.

Many publications on this subject are available. However, it is important to be aware of all possible critical conditions and the requirements set up on employed materials to master such conditions without any damage or extensive material and equipment tear-and-wear.

Thermal fatigue strength requirements are much higher for HP steam headers, which are exposed to higher temperature fluctuations, than for steam pipes.

Additionally steam headers have many welded attachments to inlet tubes from re-heaters and super-heaters. Hence, the welding integrity between header and re- & super-heater materials plays, additionally to steam temperature, very important role in material selection.

Nippon Steel has developed 9%Cr NF616 (P-92) and Sumitomo the 12%Cr HCM12A (P-122) steel which allows steam temperatures up to 620°C and pressure up to 34MPa for header applications.

Most severe conditions in the boiler undergo super-heater tubes. They must meet the stringent requirements with respect to creep-rupture strength, fire-side corrosion, steam-side oxidation, fabricability and cost-effectiveness.

With respect to creep-rupture strength, application of high-creep-strength alloys, like NF707, NF709, HR3C, Incoloy 800 and Inconel 617 for use up to 650-700°C is necessary. The highest creep-strength is achieved in Inconel 617, but this material is likely to be currently the most expensive alloy to use, due to its high Ni content.

Fire-side corrosion results from the presence of molten sodium-potassium-iron trisulfates. Resistance to fire-side corrosion increases with chromium content. The worst fire-side corrosion problems occur within steam temperature range between 600°C and 750°C.

This is because at temperatures below 600°C the trisulfates occur in solid form and above 750°C the trisulfates vaporize. Materials like Incoloy 870H, Inconel 72 or Inconel 671 are predestinated for USC applications. Another USC boiler component, which has to be seriously considered for proper material selection is the waterwall.

Latest stringent NOx requirements have led to introduction of deeply staged combustion systems, in which the air/fuel ratio is significantly under 1. In this respect, SC & USC units are more severely affected than conventional units. Cladding or weld overlays containing 18-20%Cr are necessary for USC boiler waterwalls applications.

STEAM TURBINES

ST^{s} for SC & USC duty are an extra category among the family of STs. Typical feature of modern SC turbines is relatively high capacity (250MWe - up to 1300MWe).

They are robust, heavy duty and highly sophisticated machines. Observing the main philosophy of SC plants, which is based on high efficiency, these STs are highly efficient with adiabatic efficiency up to 95%.

Cycling and start-up needs for SC & USC steam turbines to operate in a volatile electricity market puts an emphasis on the turbine's ability to handle fast loading and frequent load swings without significant loss of material life time for critical components.

Rotor cooling, turbine by-pass systems, on-line monitoring, stronger materials, and better control systems will all likely be needed. This is the crux of the challenge, especially for USC units that shall have good cycling capability, but the materials used for USC make them hard to cycle, and more prone to creep and fatigue damage. USC are particularly challenging units to cycle, and doing so calls for very careful design. Most USC power plants in Europe will be operated at base-load capacity, rather than cycled, for this reason.

Ferritic stainless steel alloys with 9-12% Cr are currently used with steam temperatures of about 600ºC. Most estimates of the upper temperature limit are about 650ºC, with high temperature strength being the limiting factor. Austenitic stainless steels maintain their strength at higher temperatures than ferritic alloys, and so were used in the early USC power plants.

However, severe thermal fatigue problems prevented their continued use at the original design temperatures and pressures. Because thermal fatigue becomes more of an issue in thicker component sections, austenitic alloys may still find use in certain thinner components.

Advanced material application, especially of titanium for the last ST blade (LSB) with lower density allows longer blades to be used and thus the exhaust annulus area to be increased. Current common high pressure SC-ST materials - comparison of SC 600°C class with conventional 538°C class is shown in Table 4.

Main steam temperature	**>600°C**	**538°C**
Rotor	**New 12 Cr forging**	**Cr-Mo-V forging**
Inner HP casing	**No 1 Cr-Mo-V-B cast steel**	**1 ¼ Cr – ½ Mo cast steel**
Inner IP casing	**12 Cr cast steel**	**1 ¼ Cr – ½ Mo cast steel**
Outer casing	**2 ¼ Cr – 1Mo cast steel**	**1 ¼ Cr – ½ Mo cast steel**
Rotating blade	**Refractory alloy (R-26)**	**12 Cr forging**
Main steam stop valve	**9 Cr - 1 Mo forging**	**2 ¼ Cr – 1Mo forging**
Main steam governing valve	**9 Cr – 1 Mo forging**	**2 ¼ Cr – 1Mo forging**

TABLE 4
MATERIALS FOR SC-ST APPLICATIONS

A major part of the USC-ST effort to successful commercial applications is the selection of alloys suitable for USC operation. Based on partial experience with USC-boilers, six following candidates have been selected for USC-ST applications, namely the ferritic alloy SAVE12, austenitic alloy Super 304H, the high Cr-high Ni alloy HR6W, and the nickel-base super-alloys Inconel 617, Haynes 230, and Inconel 740. Each of these alloys has very high strength for its type. However, they full commercial applications for USC-ST use can not be expected before year 2010.

Currently a new rotor steel having creep rupture strength suitable for withstanding steam temperatures of 600°C and higher is under development. Compared with modified 12% Cr rotor steel, the new rotor steel uses less carbon, manganese, nickel, and molybdenum content, more tungsten content, plus boron and cobalt have been added. The new steel's creep rupture strength exceeds 120 MPa at 630°C, making it applicable for rotors operating at 630°C and above. Such higher temperatures will enable significant thermal-efficiency improvements for SC & USC fossil-fuel based power plants.

BEST SC & USC INSTALLATIONS WORLDWIDE

SC & USC coal based technology is one example of a "clean coal" technique that utilizes coal more efficiently generating fewer emissions. It is an emerging technology with rather limited construction history, although it has been used more extensively during several decades in many countries worldwide

The following Figure 5 and Table 5 illustrate some selected projects representing state-of-the-art SC & USC technology with reputable efficiencies that have already been commissioned during last decade, or are currently under construction.

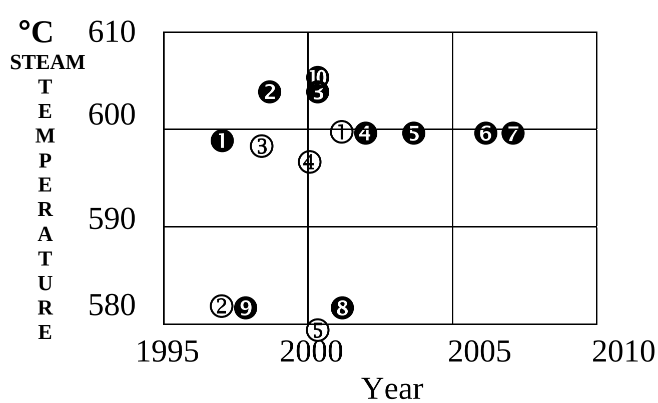


FIGURE 5
SELECTED LEADING SC & USC PROJECTS

❶Matsuura 2 (J) 598/596°C
❷Haramachi 2 (J) 604/602°C
❸Tachibana-Wan 1 (J) 605/613°C
❹Isogo (J) 600/610°C
❺Hitachinaka (J) 600/600°C
❻Torrevaldaliga (I) 600/610°C
❼Yuhuan (PRC) 600/600°C
❽ Niederhausen (D) 580/600°C
❾ Nordjyllaend 3 (DK) 582/580°C
❿ Misumi 1 (J) 605/600°C
① Tomato Atsuma (J) 600/600°C
② Skaerbaek 3 (DK) 582/580°C
③ Nanaota (J) 597/595°C
④ Tsuruga 2 (J) 597/595°C
⑤ Avedore 2 (DK) 580/600°C

No	Power Plant Name	Country	Output (MW)	Live Steam (MPa / °C / °C)	Efficiency (%)	Fuel[6]	Commercial Operation
❶	Matsuura	Japan (J)	1000	25.5 / 598 / 596		PC	1997
❷	Haramashi	Japan (J)	1000	25.9 / 604 / 602		PC	1998
❸	Tachibana-Wan-2	Japan (J)	1050	26.4 / 605 / 613	47.0	PC	2001
❹	Isogo 1 & 2	Japan (J)	2 x 500	24.5 / 600 / 600	46.0	PC	2001
❺	Hitachinaka	Japan (J)	1000	24.5 / 600 / 600		PC	2003
❻	Torrevaldaliga	Italy (I)	6 x 660	25.0 / 600 / 610	45.0	PC	2006
❼	Yuhuan	China (PRC)	2x1000	25.0 / 600 / 600		PC	2008
❽	Niederaussem	Germany (D)	1000	27.5 / 580 / 600	45.2	L	2002
❾	Nordjyllaend 3	Denmark (DK)	410	29.0 / 582 / 580	47.0	PC	1998
❿	Misumi 1	Japan (J)	600	25.0 / 605 / 600	46.0	PC	2001
①	Tomato Atsuma 4	Japan (J)	700	25.0 / 600 / 600		PC	2002
②	Skaerbaek 3	Denmark (DK)	410	29.0 / 582 / 580	49.0	NG	1997
③	Nanaoota 2	Japan (J)	700	25.5 / 597 / 595		PC	1998
④	Tsuruga 2	Japan (J)	700	25.5 / 597 / 595		PC	2000
⑤	Avedore 2	Denmark (DK)	450	30.0 / 580 / 600	49.7/48.2/ 45.0	NG/PC/ BS	2001

TABLE 5
SELECTED SC & USC POWER PLANTS IN OPERATION OR UNDER CONSTRUCTION

At present, the ultimate stage of development is fixed to live steam conditions up to 37.5 MPa / 700°C / 720°C (e.g. JOULE / THERMIE Program). Depending on the steam conditions and other process parameters (cooling method, ambient conditions, etc), thermal efficiencies in the range 50% are expected.

SUITABILITY OF SC & USC TECHNOLOGY FOR SEA REGION

The total current (2004) power generating capacity installed in SEA region[7] is around 90GW with the following fuel mix: 39% coal, 33% NG, 19% hydro, 5% oil and around 4% other renewable (geothermal, biomass, etc.- Figure 6).

The region's power generation technology includes NG & fuel oil based open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT) power plants, fossil fired ST power plants, hydro power plants, geothermal power plants and small biomass fueled plants.

[6] PC=Pulverized Coal ** L=Lignite ** NG=Natural Gas ** BS=Biomass
[7] SEA Region ⇨ Thailand, Malaysia, Indonesia, Philippines, Vietnam, Cambodia, Singapore, Myanmar, Brunei, Laos

Although National Utilities and miscellaneous IPPs place great emphasis on efficient NG-fired power plants, there are many coal-fired power plants in operation, under construction as well as in planning stage in this region. The Governments in miscellaneous SEA countries forecasts demand to grow by between 5% and 12% annually.

If demand does in fact grow at approximately 6 to 8% per year, this will mean that around 4.5-6GW power generation capacity has to be installed every year in entire SEA region.

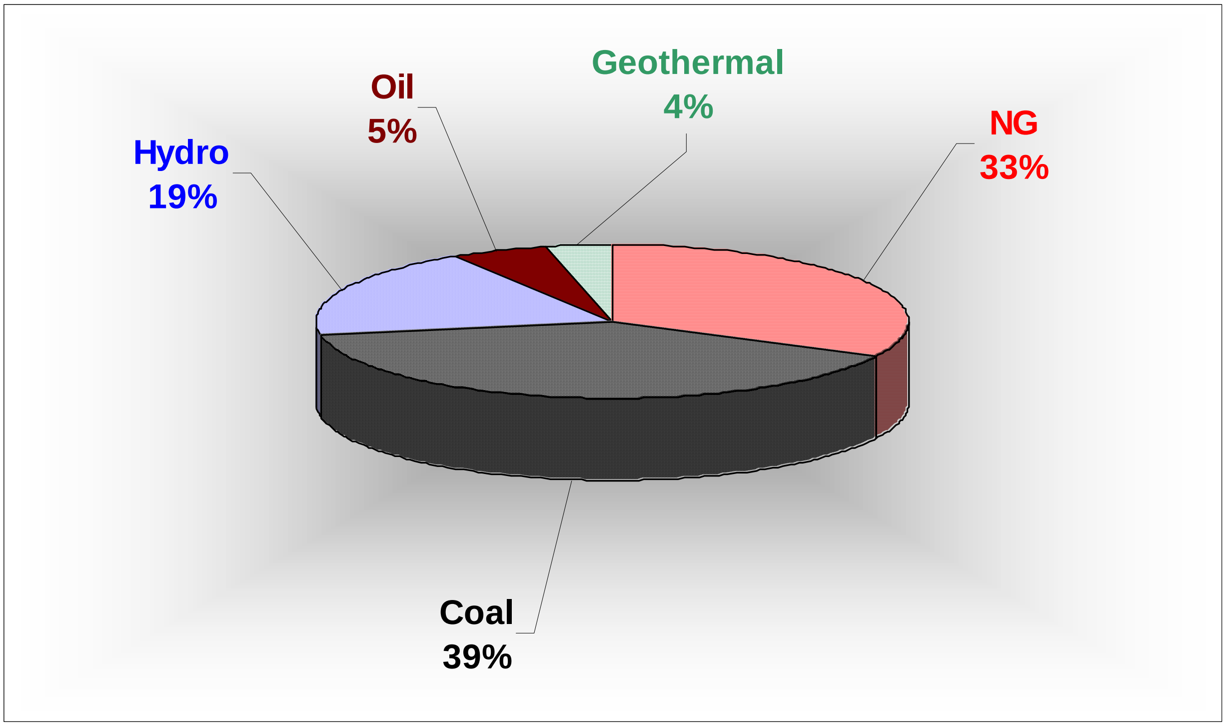


FIGURE 6
SEA POWER GENERATION FUEL SPLIT 2004

In other words, in 2004, the regional energy requirement for power generation is around 155'000 kiloton's oil equivalent (ktoe).

Considering 6% to 8% annual grow, region's energy requirements for power generation is expected to increase to about 390-520 ktoe per annum in 2020, in other terms the expected power demand in 2020 is to be around 230-300GW.

This will require putting up a huge additional power generation infrastructure. Very important question is how SEA can meet this growing power generation requirement in terms of primary energy resources in the future.

Due to limited reserves, fuel oil is not any more expected to have a major role in base load power generation.

The dependence on oil in power generation sector will be reduced in the foreseeable future, however, in log term thinking fuel oil may be maintained as important and strategic fuel for emergency power generation purposes.

Overall SEA power generation capacity (in GW and %) is shown in the diagram, Figure 7.

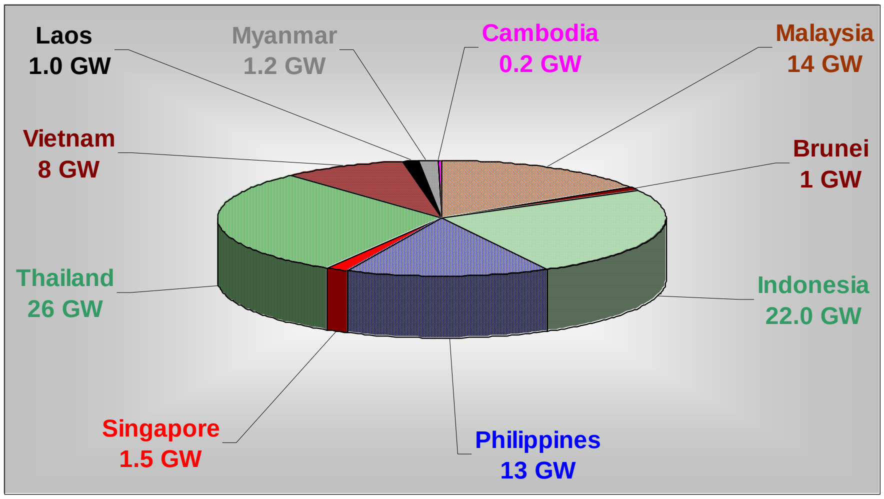
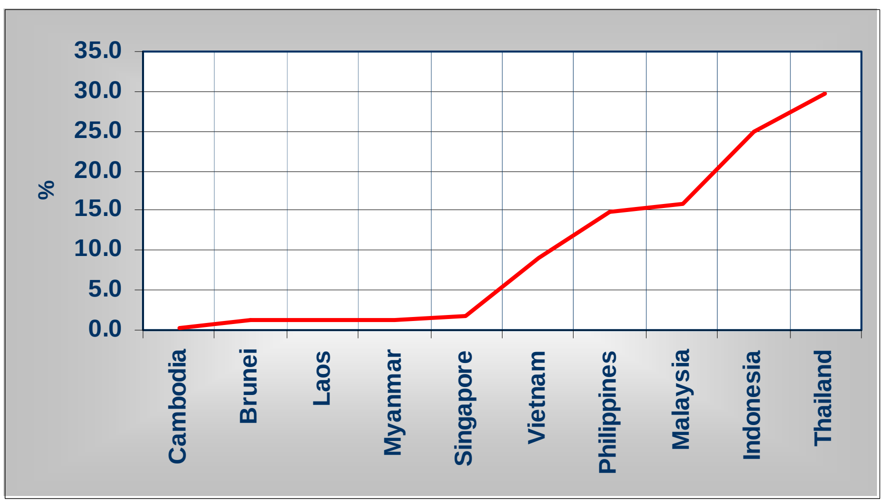


FIGURE 7
SEA POWER GENERATION CAPACITY 2004



Another very important primary energy source in SEA is NG (Figure 6). During last ten years many NG based combined cycle gas turbine (CCGT) power plants were planted by national utilities and Independent Power Producers (IPPs) in miscellaneous SEA countries, mainly in Thailand, Indonesia, Malaysia and Singapore.

This brought the NG based power generation capacity in SEA region to above 35GW. It is a fact that in the medium term future, the region will not have enough NG resources to continue covering steadily increased regional power generation needs by NG only.

Since NG has other important uses (e.g. petrochemical, chemical and fertilizer industries), the current NG resources have to be well preserved. As such it is necessary for SEA region to reduce the use of NG in the power generation.

What would be the candidate to take NG role in power generation industry? Due to very long transmission distances and other related problem, accessible hydro resources in many SEA countries, except Vietnam, Myanmar and Kampuchea, are rather limited.

Other renewable energies (geothermal, solar, wind, biomass) will not play major role in the foreseeable period and nuclear energy is still not an acceptable alternative in many SEA countries.

The answer to above question is simple. Hydro, coal and biomass represent future potential energy resources in this region. SEA has some coal reserves, most of it in Indonesia and Vietnam. Coal reserves in other SEA countries are rather small.

However coal is available in large quantities worldwide and its price is relatively stable. Total world proven recoverable coal resources amount to 985'000 million metric tons (more than 25% located in Asia and about 8% in Australia).

The current worldwide coal consumption is 4'400 millions metric tons per annum. Even if an average consumption increases 5% each year, the proven coal resources are sufficient to cover coal consumption for more than 110 years.

Coal is a primary energy that is available at reasonable price in Asia. In order to achieve power generation security at affordable and competitive prices, coal contribution to power plant mix in SEA has to be increased.

On the other hand, in many SEA countries coal is an imported fuel, therefore it has to be used wisely and efficiently; the power generation scene will not be complete if some important considerations such as power generation efficiency and quality are not widely discussed.

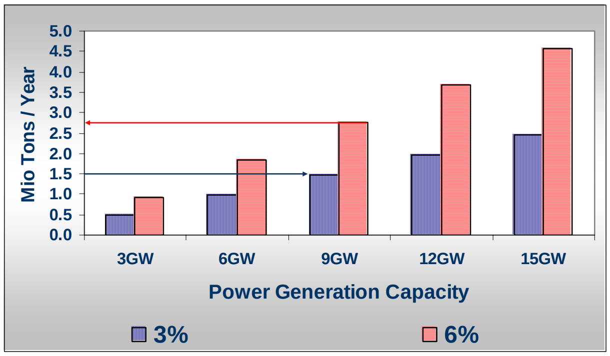
For example average 3-6% efficiency improvement achieved by SC technology (in comparison to sub-critical power generation technology) results in an annual saving of approximately up to 3 millions metric tons of coal (Figure 8) or between 50 and 85 Mio US$ (Figure 9) per each 9 GW power generation capacity[8] .

In other words a saving of <u>5.5 – 9.4 Mio USD / Year / 1000MW power plant</u>.

[8] Basic data used for this calculation: Coal LHV = 30'000 MJ/ton, average yearly load factor 85%, power plant efficiency=39%, coal price 30 US$/ton.

There are many challenges to be faced in SEA's power generation sector - in sourcing the energy, in terms of keeping its price down and in reducing its effects on the environment as the entire region is moving towards full industrialization and economical growth.

<u>SC & USC technology may have a bight future in SEA as far as the whole region will take all available power generation alternatives seriously in to consideration.</u>



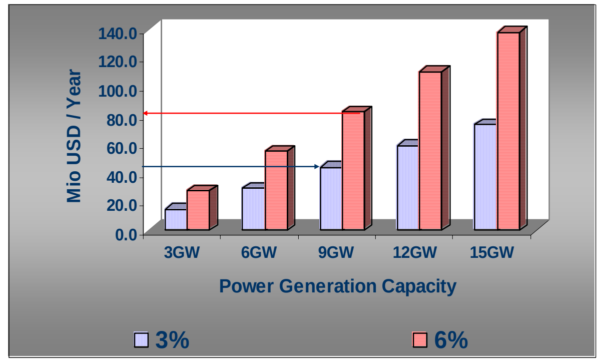
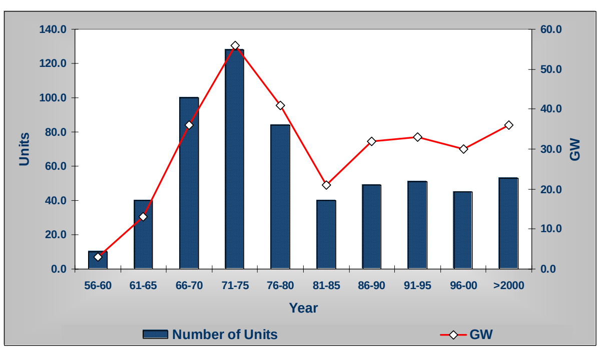


FIGURE 8
COAL SAVINGS

FIGURE 9
OPERATIONAL COST SAVINGS

For better illustration and reference, following diagram, Figure 10, shows development of SC & USC power plant installation during individual half-decades from 1956 till 2004and Figure 11 shows total SC & USC power generation capacity and number of power plants installed worldwide during last decade.



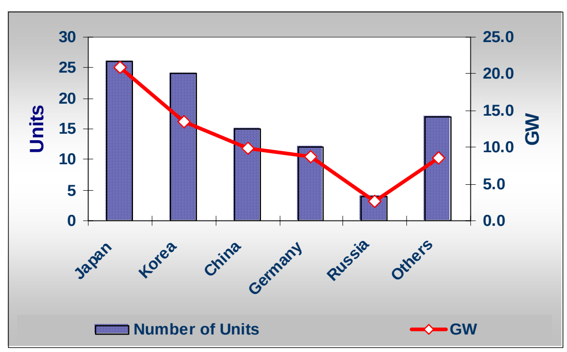


FIGURE 10
SC & USC POWER GENERATION CAPACITY 1956-2004

FIGURE 11
SC & USC POWER GENERATION CAPACITY 1995 - 2004

Interesting, but not surprising, fact is the average unit size that has been growing from around 200-300MW in 1956-60 to 500MW in 1976-85 and 700MW after 2000 (Figure 10).

Very important factor in present development of SC & USC technology is the most progressive development in East-Asia (Figure 11). <u>Will SEA follow its East-Asian neighbors?</u>

It is important that all of these issues are properly addressed in order for the region to maintain its growth and economy.

CONCLUSIONS & CONSTRAINTS

The world's power-generation industry currently uses various technologies to utilize coal efficiently and cleanly.

The SC & USC technology increases the thermal efficiency of power plants burning pulverized coal at least by 3 to 6% (relative) in comparison to conventional power plant technology with sub-critical steam conditions and in this way it makes a significant contribution to global efforts to reduce greenhouse gases.

The early problems experienced with the first and second generation of SC & USC power plants is underway to be overcome.

Currently, USC power plants with steam conditions up to 30MPa, 600°C / 620°C have been matured and become high efficiency commercialized technology.

This is indicating that SC & USC coal fired power plants will have broad prospects of development in this centaury, and in conjunction with conventional desulphurization and denitrification further perfected, will still combine to give high efficiency and clean coal firing power generation technology.

Outlook for coal based SC & USC power plant technology is very positive and its further growth lies ahead. Intensity of this growth will depend on the following major factors:

- On a worldwide basis, the prospect for SC & USC technology is extremely good, especially in rapidly developing markets such as Asia.
- Several Asian countries using coal for base load power generation (e.g. Japan, China, India, and South Korea) have already large manufacturing capacity in the components common to conventional and SC units and are now intensifying the existing or building up new capacity in those components that are specific to supercritical technology.
- SC power plants have attained similar or even higher availability factor as conventional power plants.
- Thermal efficiency is increased with higher steam parameters. It is generally considered that SC power plants will have about 2-3% and USC about 3-6% higher efficiency than conventional power plants. If conventional 5GW power generation capacity is replaced by SC or USC technology, between 1 and 2 Mio tons of coal can be saved ever year (approximately 30-60MioUSD/Year).

- Even if construction of an USC power plant costs around 10% to 15% more than a comparable-scale conventional power plant design, the additional expense is more than offset by fuel savings.

  Evaluations have concluded that the capital cost of the boiler and ST in an USC power plant can be up to 50% higher than conventional components, and the USC power plant will still be cost-competitive, this means that the Life Cycle Costs of SC & USC power plants are lower than those of conventional plants.
- SC & USC power plants can maintain relatively high efficiency at rather low load.
- There are no operational limitations due to SC & USC once-through boilers compared to conventional drum type boilers. SC & USC power plants have better operational dynamics. i.e. their ramp rates are higher, namely 7-8%/min compared to about 3-5%/min for conventional units at higher loads.
- Once-through boilers do not have a boiler blow-down. This has a positive effect on the water balance of the power plant with less condensate needing to be fed into the water-steam cycle and less waste water to be disposed of.
- Due to lower specific (tons/MWh) coal consumption the emissions of CO_2, SO_2 and NOx are proportionally reduced.

On the other side there are some constrains related to coal fueled SC & USC technology that are summarized in the following:

- ✓ If SC & USC power generation technology is to become one of the preferred choice in new power plant construction, it has to become economic against the alternative technologies such as subcritical coal-fired conventional power plants and NG-fired CCGT power plants.
- ✓ Advanced austenitic stainless steels for use as superheater and reheater tubing are available for service temperatures up to 650°C and possibly 700°C. Ni base superalloys would be needed for higher temperatures. None of these steels have been approved by the ASME Boiler Code Group so far.
- ✓ Higher strength materials are needed for upper water walls of boilers with steam pressure of 24 MPa (240 bar) and higher.
- ✓ Ferritic materials will be replaced by nickel-based super-alloys for USC applications as steam conditions are increased. This changeover point is an issue still to be resolved.

- ✓ Better understanding of maintenance needs of the USC boiler & ST and related auxiliary systems is essential for long-term, reliable operation.

Coal based SC power generation technology is matured and advanced technique that can be favorably compared with well proven conventional power generation technology. USC takes all advantages of well proven SC technology and is continuously build-up on this strong SC foundation.

In the medium to long term, as NG and fuel oil become a more scarce fuel and prices increase, and in conjunction with further economic improvements in clean coal technologies, SC & USC technology can expect to receive a renaissance as a feasible option for new large scale coal fueled power generation plants.

There is no solution capable meeting of our all future energy requirements. Instead the answer will come from a family of diverse New Technologies which will have an impact on everything — from environmental quality to costs that consumers will ultimately have to pay.

REFERENCES

[1] Compatibility of Advanced Power Generation Technologies with the Independent Power Production; A S M E TURBO EXPO LAND, SEA & AIR, STOCKHOLM, SWEDEN JUNE 1998; Miro R. Susta & Peter Luby, IMTE AG-Switzerland

[2] Power Generation Technological Determinants for Fuel Scenario Outlook; ASME TURBO EXPO LAND, SEA & AIR, STOCKHOLM, SWEDEN JUNE 1998;Peter Luby & Miro R. Susta, IMTE AG-Switzerland

[3] Contribution of IGCC & PFBC to Global Fuel Consumption Trends; POWERGEN-EUROPE 1998, MILAN, ITALY, JUNE 1998; Peter Luby & Miro R. Susta, IMTE AG-Switzerland

[4] Steam Power Plants – New Wave of Supercriticality; POWERGEN-EUROPE 2002, MILAN, ITALY, JUNE 2002; Miro R. Susta & Peter Luby, IMTE AG/Ingchem-Switzerland/Slovak Republic

[5] Supercritical Steam Power Plants - an Attractive Option for Malaysia; MALAYSIA POWER 2003, KUALA LUMPUR, MALAYSIA, APRIL 2003; Miro R. Susta & Peter Luby, IMTE AG/Ingchem-Switzerland/Slovak Republic

[6] Advanced Clean Coal Technology for Power Generation- An Opportunity for Southeast Asia; MALAYSIA POWER 2003, KUALA LUMPUR, MALAYSIA, APRIL 2003; Miro R. Susta & Dr. Sohif Bin Mat, IMTE AG/Transtherm Sdn Bhd-Switzerland/Malaysia

[7] Development of Ultra Super Critical PF Power Plants in Denmark; Marius NOER & Swen KJÆR; Vestkraft Power Company and ELSAMPROJEKT; Denmark

[8] A Vision for Thermal Power Plant Technology Development in Japan; HISA, Shoichi Hisa, Masakuni Sasaki, Masafumi Fukuda & Michio Hori; TOSHIBA CORPORATION Tokyo, Japan

[9] Advanced 700°C PF Power Plant 2003; J. Bugge, Tech-wise A/S-Denmark

[10] Develop Supercritical Coal Fired Units to Optimize China's Thermal Power Structure; Zhao Zongrang & Li Guanghua, State Power Corporation of China-PRC

[11] Ultra-Supercritical Steam Turbines: Next-Generation Design and Materials; EPRI Journal April 2002, USA

[12] Ultra-Supercritical Steam Corrosion; Gordon R. Holcomb, U. S. Department of Energy, Albany Research Center, USA

AUTHOR'S BIOGRAPHICAL SKETCH

Miro R. Susta is graduate of Swiss Federal Institute of Technology in Zurich, ETHZ; Diploma (M.Sc.) degree in Power Plant Mechanical Engineering.

He is a Member of Swiss Engineers and Architects Association (SIA) and Member of American Society of Mechanical Engineers (ASME).

Mr. Susta has more than 28 years of professional experience in power plant design & engineering, field and factory testing, sales and marketing with Sulzer-Brown Boveri Turbomachinery AG, Brown Boveri AG, Motor Columbus Consulting Engineering AG, Asea Brown Boveri AG in Switzerland and NEI Parsons in England and Malaysia.

In year 1992, Mr. Susta joined Swiss consulting engineering company IMTE AG, which is specialized in thermal power generation consulting engineering activities.

With IMTE AG, he was involved in Lumut 1303MW CCGT, Sepang 710 MW CCGT and Tanjung Bin 2100MW Coal Fired Power Plant Project in Malaysia and Vembar 1800MW CCGT Power Plant Project in India.

In 2003 Mr. Susta was appointed by United Nations Organization, UNIDO, for development of small biomass and biogas fired power plants in Tanzania.

At the present, Mr. Susta is seconding Zelan Holdings (M) Sdn Bhd, Malaysia in their international business activities related to power generation.