Application and development prospects of double-reheat coal-fired power units

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

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Abstract

Most pulverised coal combustion (PCC) plants employ single-reheat cycles. However, double-reheat cycles can significantly improve the electrical efficiency of PCC plants. Surprisingly, no double-reheat units have been commissioned since the 1990s. However, with rising primary energy costs, more stringent emission limits and advances in thermal power engineering, double-reheat cycles are being considered to minimise the cost of electricity, reduce emissions and prolong valuable coal supplies, especially in China. This report reviews, analyses and assesses the application and development prospects of coal-fired double-reheat units.

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Acronyms and abbreviations

ASME	American Society of Mechanical Engineers
AUSC	advanced ultra-supercritical
BEST	back pressure extraction turbine
BFP	boiler water feed pump
CHP	combined heat and power
CCGT	combined cycle gas turbine
CCHPLA	cross compound at high/low position arrangement
CCS	carbon capture and storage
CPI	consumer price index
EPC	engineering, procurement and construction
EVAP	evaporators
FEED	front end engineering design
FSDP	full-scale demonstration plant
HHV	higher heating value
HP	high pressure
IDC	interest during construction
IP	intermediate pressure
LCOE	levelised cost of electricity
LHV	lower heating value
LP	low pressure
O&M	operation and maintenance
P&ID	piping and instrumentation diagram
PCC	pulverised coal combustion
PFD	process flow diagram
R&D	research and development
SCR	selective catalytic reduction
USC	ultra-supercritical
VHP	very high pressure

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1 Introduction

Pulverised coal combustion (PCC) power plant dominate the power industry and will continue to do so for the foreseeable future. Increasing PCC plant electrical efficiency lowers coal use, resulting in reduced fuel costs, and helps to sustain valuable coal resources. A higher electrical efficiency also reduces the amount of flue gas to be treated in the flue gas cleaning systems, and lowers taxes or fines related to emissions of carbon dioxide. A higher electrical efficiency also favours the economic viability of carbon capture and storage (CCS).

From the 1880s to the 1950s, PCC power plant operated at subcritical steam conditions and employed a single circuit of steam through a boiler and turbine. In the early 1950s, there was rapid growth in the average unit size of PCC units and a single steam reheat loop was introduced. This single-reheat steam cycle takes steam exiting the highest pressure module in the steam turbine and reheats it in the boiler before entering the second highest pressure module in the turbine. Single-reheat increases electrical efficiency by a few percentage points by increasing the average temperature of the steam across the turbine. The single-reheat steam cycle became the standard steam cycle design for PCC units. Single-reheat cycles require additional boiler and turbine components, which increases capital expenditure. However, the additional costs are paid for with savings on fuel costs.

In the late 1950s, a second reheat loop was established. This double-reheat steam cycle takes steam exiting the second highest pressure module in the steam turbine and reheats it in the boiler before entering the third highest pressure module in the turbine. Double-reheat increases electrical efficiency over single-reheat by one to two percentage points. Again, the additional steam reheat loop increases the capital costs, which is paid for with fuel savings.

Sixty coal, oil- and gas-fired double-reheat units have been built globally, 37 of which are coal fired. This number is small compared to the roughly 8700 built coal-fired units globally. Despite the fact that the world's most efficient coal-fired power unit, Nordjylland unit 3 commissioned in 1998 in Denmark, employs a double-reheat cycle, less than 0.5% of the global coal fleet uses double-reheat technology.

Chapter 2 of this report explains how double-reheat cycles increase the efficiency of coal-fired power plant. Chapters 3 to 7 review and analyse the technical and economic performance of operational and decommissioned coal-, oil- and gas-fired double-reheat units in Germany, the USA, Italy, Japan and Denmark, respectively. Chapter 8 evaluates the use of double-reheat units globally and presents development trends. Chapter 9 reviews the recent technical developments and advances in turbines, boiler configuration and steam cycles for double-reheat units. Chapter 10 evaluates the double-reheat units that are currently in planning and under construction. Finally, Chapter 11 reviews the research and development (R&D) programmes for advanced ultra-supercritical (AUSC) coal-fired power plant with the prospect for double-reheat steam cycles.

2 Electrical efficiency

PCC plant transfer heat energy from the boiler to the turbine via the steam cycle. The steam cycle, which is a type of heat engine, operates broadly under the thermodynamic principle of a Carnot cycle, but in a modified form known as the Rankine cycle when water is used as the working fluid. The steam cycle can be made more efficient by reducing losses. For a unit operating with a superheat steam temperature of 600°C, efficiency losses in the steam cycle account for around 10% points of electrical efficiency. The steam cycle can be made more efficient by: employing regenerative feedwater preheating; combustion air preheating; raising the maximum steam temperature; reducing the turbine exit temperature; and steam reheating. Henderson (2004) presents a report titled 'Understanding coal-fired power plant cycles' for further reading.

2.1 Maximum steam temperature and pressure

Steam cycle efficiency is proportional to the equation $(T_{MAX}-T_{MIN})/T_{MAX}$, where T_{MAX} is the main superheater steam temperature and T_{MIN} is the turbine exit temperature (both measured in Kelvin). Therefore, to increase the steam cycle efficiency the superheater steam temperature must be increased and the turbine exit temperature decreased.

The main superheater temperature is limited by materials that can operate in these components at these temperatures for a practical length of time without failure. Increasing both the superheater and reheater temperatures by 20°C equates to an increase of roughly 1% point in net efficiency (National Coal Council, 2007). Significant gains in electrical efficiency can be made by increasing the superheated steam temperature up to approximately 900°C. Nicol (2013, 2014) explains the historic increase in superheat temperature with steels and the current research into nickel alloys.

The turbine exit temperature is determined by the temperature of the cooling fluid, which can be river water (directly or using cooling towers), sea water or ambient air. In Europe, a PCC plant with sea water cooling has 1.5–2% points higher efficiency than an equivalent plant using river-water cooling (VGB, 2012). The turbine exit temperature is constrained geographically.

For single reheat cycles, improvements in steam cycle efficiency by increasing the superheat steam pressure are less useful than increasing superheat steam temperature. Increasing superheat steam temperature from 600°C to 700°C results in efficiency rise of 2.2% points, whereas increasing the pressure from 25MPa to 35MPa results in an efficiency rise of 0.8% points (Mao, 2012). However, Kjaer and Drinhaus (2010a) show that the thermodynamic gain by increasing main steam pressure of double-reheat cycles is more than twice the gain of the single reheat cycles.

Generally, the electrical efficiency differences between individual plants may vary due to process differences, such as coal calorific value, auxiliary load, number of reheats and temperature of condenser cooling medium. It is important that the basis on which efficiency is calculated is clearly stated and consistent: for example, which heating value for the fuel is used. Efficiency measured on a higher heating value (HHV) basis can be nearly 2% points lower than calculated on a LHV basis for bituminous coals and 6% points lower for many lignite coals (Henderson, 2015). The Association of German Engineers have developed a standard, known as VDI3986 'Determination of efficiencies of conventional power stations', which provides a method of calculating the electrical efficiency of thermal power plants so they are comparable internationally (Drinhaus, 2015).

Electrical efficiency can also be represented by heat rate, which is the amount of heat consumed in the boiler to produce 1 kWh of electricity. Heat rate is expressed as kJ/kWh and is related to electrical efficiency by dividing the heat rate by 3600.

Figure 1 shows a plot of net electrical efficiency (LHV) with main steam temperature for operating and planned PCC units. These units are all seawater cooled, fire the same type of coal, but vary in steam pressure and temperature, final feedwater temperature, the water/steam cycle design and components used at the time of construction. The black line shows that the efficiency of operational PCC units increases with rising steam temperature. The blue line shows the maximum efficiency increase with rising steam temperatures of the steam cycle, assuming no auxiliary load and ideal components (no losses) (Kjaer and Drinhaus, 2010a).

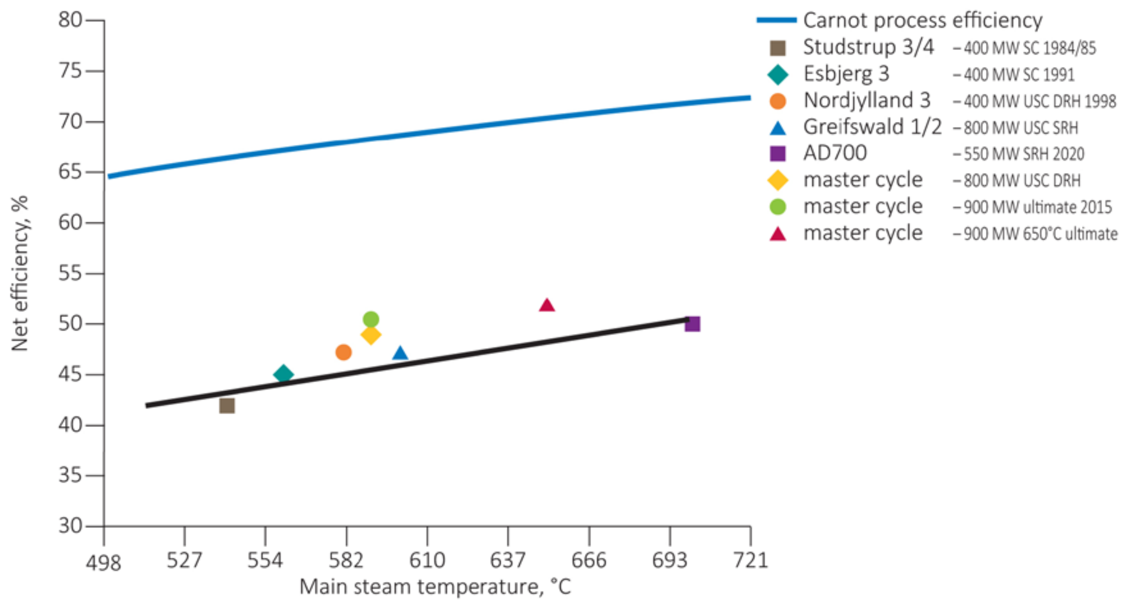

Figure 1 Net efficiency (LHV) with main steam temperature (Kjaer and Drinhaus, 2010a)

2.2 Steam reheating

Adding reheat steam loops increases the efficiency by increasing the average upper temperature of the steam cycle. Single-reheat steam cycles are common, double-reheat steam cycles rare, and a third reheat steam loop is impractical.

2.2.1 Single circuit

Until the late 1950s, PCC units employed a single circuit of water/steam in the steam cycle. The heat exchangers in the boiler consist of an economiser, waterwall and superheater. The steam cycle in drum-type boilers is shown in Figure 2. Water is pumped through the economiser into the steam drum. From the steam drum water is either pumped (forced circulation) or flows due to density differences (natural circulation) through the water walls, where the water boils. The water/steam mixture re-enters into the steam drum. Steam from the steam drum then passes to the primary and secondary superheater in the boilers. PCC unit design varies and some boilers may simply employ one superheater pass.

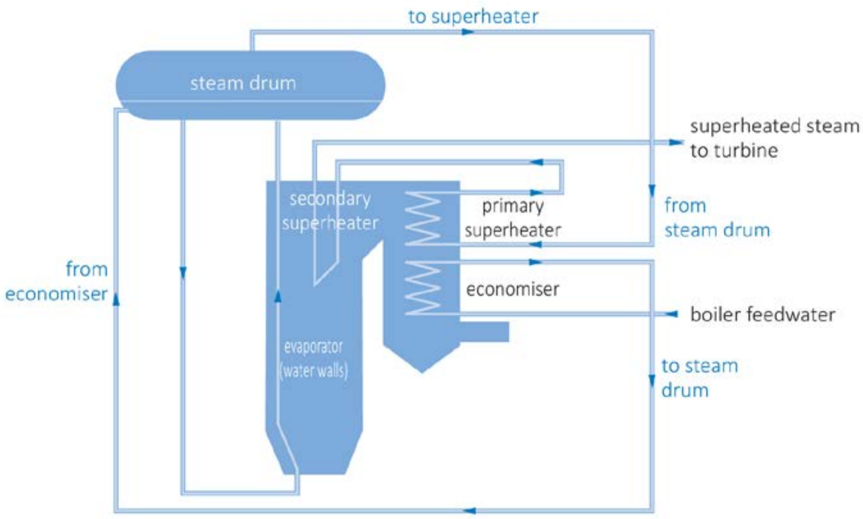

Figure 2 Steam cycle in drum-type boiler (Henderson, 2004)

2.2.2 Single-reheat

A single steam reheat loop was established in the early 1950s. The extra steam loop takes steam from the high pressure (HP) module and reheats it in the boiler before returning it to the intermediate pressure (IP) turbine module. Simultaneously, developments in high temperature materials allowed boilers to operate with supercritical steam conditions, which led to once-through steam cycles. The steam cycle in a once-through supercritical boiler is shown in Figure 3. During start-up and low load operation, before the once through operation point, a levelling vessel and separators, placed after the waterwall, perform a similar role to the steam drum in the no-reheat cycle.

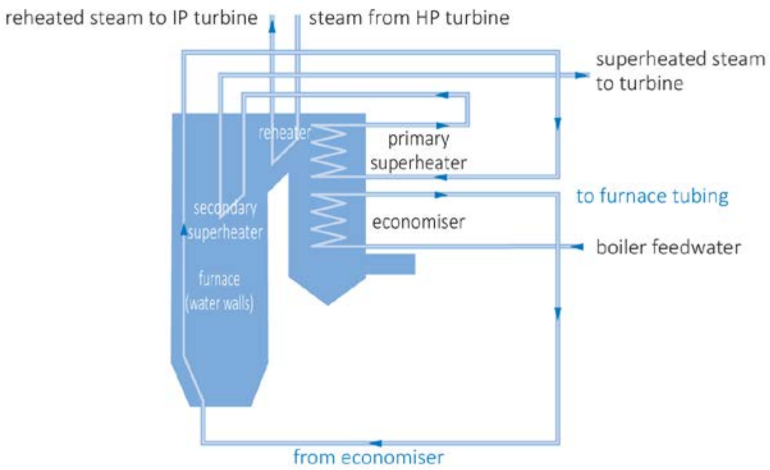

Figure 3 Steam cycle in once-through single-reheat supercritical boiler (Henderson, 2004)

Single-reheat increases electrical efficiency by a few percentage points. Single-reheat cycles require an additional reheater in the boiler, two extra high temperature steam pipes, from the turbine to the boiler, and a modified steam turbine. This increases capital expenditure, but the additional costs are quickly paid for with decreased operational expenditures.

2.2.3 Double-reheat

A double-reheat steam cycle was introduced with the early supercritical boilers in the late 1950s. The double-reheat cycle adds another steam reheat loop to the single-reheat, which can require an additional turbine module. This increases electrical efficiency by 1–2% points. Figure 4 shows a process flow diagram of a modern double-reheat PCC unit (Xu and others, 2015; Li and others, 2014).

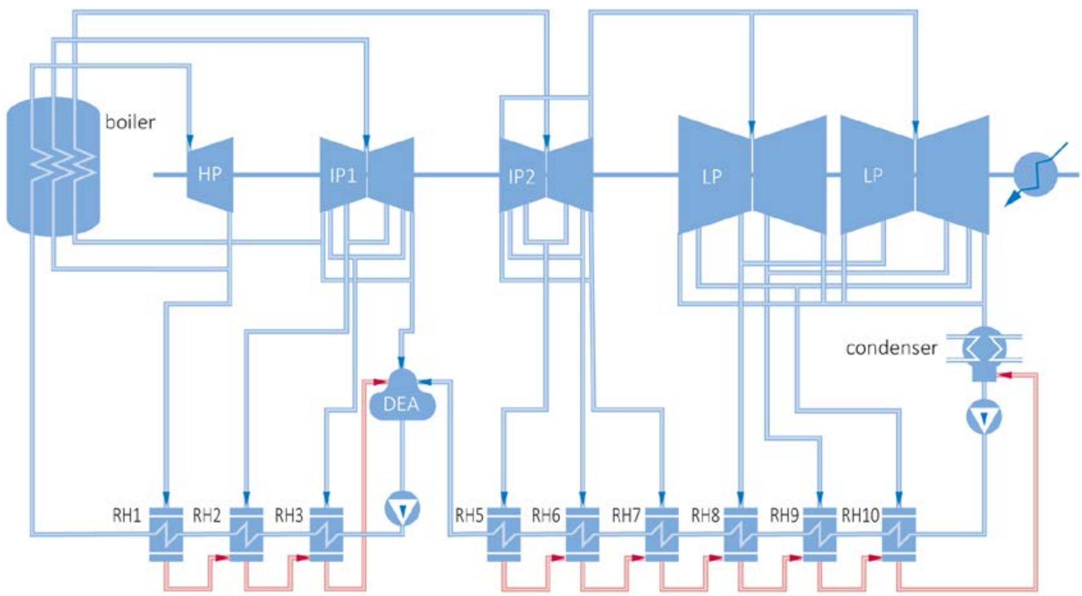

Figure 4 PFD of a standard double-reheat steam cycle (Xu and others, 2015; Li and others, 2014)

Figure 5 is a plot of superheater steam temperature (°C) and carbon dioxide emissions (gCO_2/kWh) with efficiency. The green line shows that efficiency increases with superheat steam temperature and the orange line shows that CO_2 emissions decrease with increasing superheater temperatures and efficiency. State-of-the-art PCC plant are also shown on this figure with the associated steam conditions in the following format: superheater steam temperature (°C) / reheat temperature (°C) / second reheat temperature (°C) / superheater pressure (MPa); for example 600°C /620°C /620°C /31 MPa. Throughout this report the steam conditions will be presented in this format and all efficiencies are net electrical, on a lower heating value basis for coal, unless stated otherwise.

Figure 5 illustrates the efficiency gain of double-reheat technology combined with cold sea water cooling found at Nordjylland 3 ultra-supercritical (USC) PCC plant, compared to other higher temperature single-reheat PCC plant. For modern PCC units operating at ultra-supercritical (USC) steam conditions, reheated steam has significantly lower pressure than superheat steam, at around 5–8 MPa, depending on the HP design and numbers of reheats, and slightly higher temperature, typically by 10–20°C.

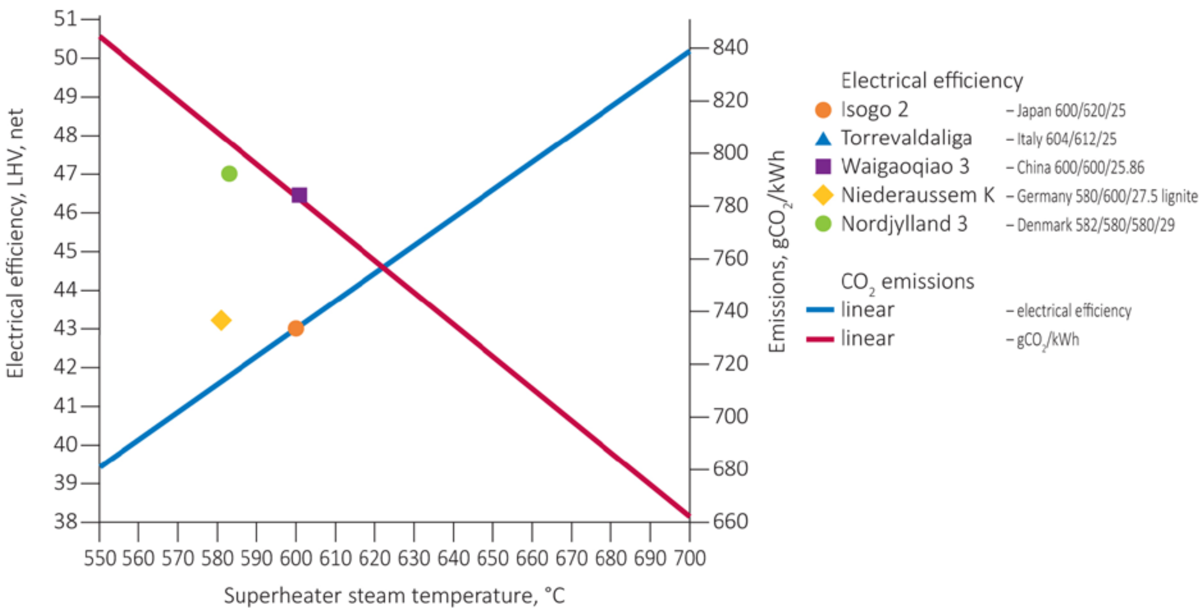

Figure 5 Relationship between steam temperature and electrical efficiency (Nicol, 2013)

2.3 Auxiliary load and components

Electrical efficiency is lost to the auxiliary load and internal losses. The auxiliary load is the power required by electrical devices to operate the PCC plant. Significant auxiliary loads include the coal pulverising mills, motor driven boiler feed water pumps (BFP), forced and induced draught fans, particulate control devices and pumps in flue gas desulphurisation units. Internal losses are heat losses due to friction in moving components, such as motor driven BFPs, forced and induced draught fans, the electricity generator and turbine bearings. For a unit operating with superheat steam temperature at 600°C, efficiency losses to the auxiliary load and component inefficiencies equate to around 10% points of electrical efficiency (MPS, 2008). Electrical and mechanical improvements in components have reached a point of diminishing returns, and component losses can no longer be significantly reduced. However, components need cooling and this heat can be used in the water/steam cycle to raise electrical efficiency by approximately 0.1% point.

3 Status of double-reheat units in Germany

Chapters 3 reviews and analyses the technical and economic performance of operational and decommissioned double-reheat units in Germany. The technical aspects include the process design, start-up mode, reliability, availability, control mode, and the effect of parameters such as reheat steam temperature and any technical difficulties.

3.1 Hüls 1

The first supercritical coal-fired double-reheat unit in the world, Hüls unit 1, was commissioned in 1956 in Hüls AG chemical factory, located in Marl (Germany). The 104 MWe unit had the following steam conditions 600°C/560°C /510°C /30 MPa, the primary reheat pressure was 10.7 MPa, and the heat rate was 2080 kcal/kWh (8709 kJ/kWh) (Meier, 2015).

3.2 Gaisburg 4

Gaisburg unit 4 was a gas-fired double-reheat unit commissioned in 1958 and now decommissioned. It was owned by ENBW Energie Baden-Wurttemberg. Siemens manufactured the boiler and turbine. The 100 MWe unit had subcritical steam conditions of 540°C/540°C/520°C/17.8 MPa (Platts, 2014).

3.3 Ratingen 1

Ratingen unit 1 was a coal-fired double-reheat unit commissioned in 1962. It was owned by Durr Werke Ag. The 103 MWe unit had supercritical steam conditions of 525°C/535°C/535°C/25.5 MPa (Bertilsson and Scarlin, 1990).

3.4 Wedel 3

Wedel unit 3 was a coal-fired double-reheat unit commissioned in 1963 and now decommissioned. It was owned by ENBW Energie Baden-Wurttemberg. Siemens manufactured the boiler and Durr manufactured the turbine. The 155 MWe unit had supercritical steam conditions of 540°C/540°C/520°C/24.6 MPa (Platts, 2014).

3.5 Franken II 1 and 2

Franken II units 1 and 2 were coal-fired double-reheat units commissioned in 1966 and 1967 respectively and now both decommissioned. They were owned by E.On Bayern. Siemens manufactured the boiler and turbine for unit 1. Siemens manufactured the boiler for unit 2 and MAN manufactured the turbine. The two 206 MWe units had steam flow rates of 151.2 t/h each, steam conditions of 530°C/540°C/540°C/24.5 MPa and reached a net efficiency of 39.4% (LHV) (Platts, 2014).

3.6 Grosskraftwerk Mannheim 4

Grosskraftwerk Mannheim unit 4 is a supercritical, hard coal-fired double-reheat unit commissioned in 1970. Deutsche Babcock Anlagen manufactured the boiler and ABB Power Generation manufactured the turbine. The supercritical 220 MWe unit has steam conditions of 530°C/540°C/530°C/25 MPa and reaches an assumed net electrical efficiency of 39.4% (LHV) (IEA CCC, 2012).

3.7 Grosskraftwerk Mannheim 7

Grosskraftwerk Mannheim unit 7 is a supercritical, hard coal-fired double-reheat unit commissioned in 1982-4. EVT Energie- und Verfahrenstechnik manufactured the boiler and ABB Power Generation manufactured the turbine. The supercritical, 475 MWe unit has steam conditions of 530°C/540°C/530°C/25.6 MPa and reaches an assumed net electrical efficiency of 39.6% (LHV) (IEA CCC, 2012; Bertilsson and Scarlin, 1990).

3.8 Sandreuth 1, 2 and 3

Sandreuth consists of three gas-fired units each of 25 MWe commissioned in 1982. EVT Energie- und Verfahrenstechnik manufactured the boilers and ABB Power Generation manufactured the turbines. The steam conditions are 535°C/360°C/400°C/12 MPa and the units reach an assumed net electrical efficiency of 28.1% (IEA CCC, 2012).

3.9 Analysis

Germany was the first country to employ double-reheat steam cycle technology. In the 26 years from 1956 to 1982, eleven double-reheat units were commissioned. These units are made up of six hard coal-fired and four gas-fired units, amounting to 1.64 GWe. Table 1 lists the eleven double-reheat units built in Germany, with details of year commissioned, primary fuel, size (MWe), steam conditions (°C/°C/°C/MPa) and electrical efficiency, most of which are assumed values), in chronological order of year commissioned.

Table 1 List of double-reheat units in Germany

Unit	Commissioned	Primary fuel	Size (MWe)	Steam Conditions (°C/°C/°C/MPa)	Efficiency (%)
Hüls 1	1954	Hard coal	100	600/560/510/30	
Gaisburg 4	1958	Gas	100	540/540/520/17.8	
Ratingen 1	1962	Hard coal	103	525/535/535/25.5	
Wedel 3	1963	Hard coal	155	540/540/520/24.6	
Franken II 1	1966	Hard coal	206	530/540/540/24.5	39.4
Franken II 2	1967	Hard coal	206	530/540/540/24.5	39.4
Mannheim 4	1970	Hard coal	220	530/540/530/25	39.4
Mannheim 7	1982	Hard coal	475	530/540/530/25	39.6
Sandreuth 1	1982	Gas	25	535/360/400/12	28.1
Sandreuth 2	1982	Gas	25	535/360/400/12	28.1
Sandreuth 3	1982	Gas	25	535/360/400/12	28.1

Hüls unit 1 had the highest superheat and reheat temperature and superheat pressure at 600°C, 560°C, 510°C and 30 MPa respectively. The following five coal-fired units settled on 530°C/540°C/530°C/25 MPa over the next 26 years. The steam conditions were decreased because of inexperience with austenitic steels at high supercritical steam conditions; this unit de-rate was not unrelated to the number of reheats. Metallurgists initially thought austenitic steels could be used for thick-section components at superheat temperatures up to 650°C. Siemens manufactured four boilers and three turbines, EVT Energie- und Verfahrenstechnik manufactured four boilers and ABB Power Generation manufactured four turbines (Platts, 2014; IEA CCC, 2012).

Figure 6 shows a graph of the electrical efficiency and unit size with year commissioned for hard coal-fired units. The unit size increased from 100 to 475 MWe, and the electrical efficiency almost reached 40% (Platts, 2014; IEA CCC, 2012).

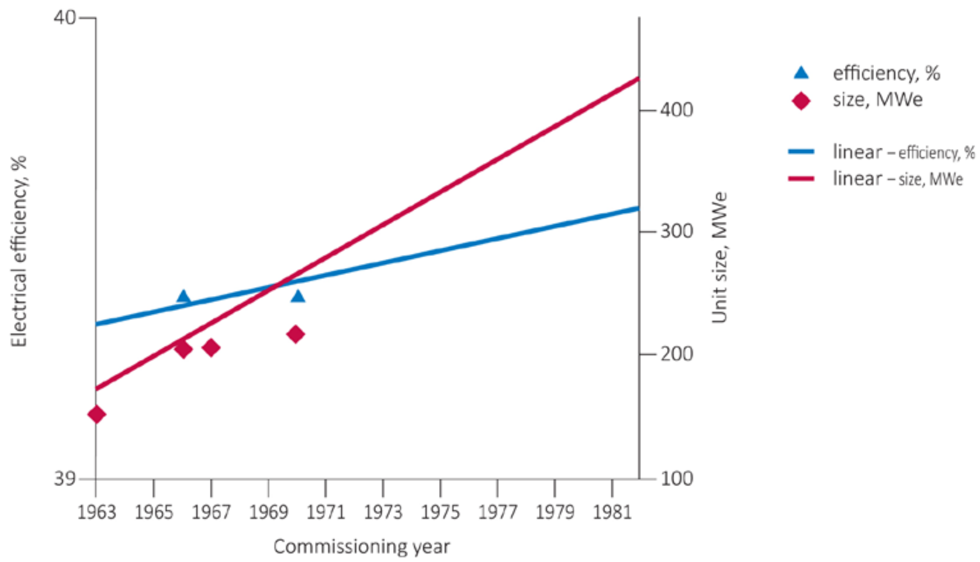

Figure 6 Efficiency and unit size of double-reheat units in Germany (Platts, 2014; IEA CCC, 2012)

A double-reheat cycle has not been built in Germany since 1982. At the time this was because of the additional costs coupled with difficulties in mid-range load operation found with early double-reheat units in Germany (VGB 1995)

4 Status of double-reheat units in the USA

Chapter 4 reviews and analyses the technical and economic performance of operational and decommissioned double-reheat units in the USA.

4.1 Philo 6

Philo unit 6 was the first supercritical double-reheat unit commissioned in 1957 in south-eastern Ohio. Owned by American Electric Power (AEP), the 120 MWe unit operated at the following steam conditions 621°C/565°C/538°C/31 MPa, and reached 40% electrical efficiency. The boiler was manufactured by Babcock & Wilcox and General Electric manufactured the turbine. The cost of building the unit was $20.3 million in 1957 (170 $/kW), which was 20% more than the estimated cost of a conventional subcritical unit of the same capability. Philo unit 6 was mothballed in 1975, decommissioned in 1979 and demolished in 1983, after 103,110 operating hours. The unit was demolished because it was uneconomic to upgrade the plant to comply with the requirements of the Clean Air Act (Weitzel, 2012a; ASME, 2003a).

4.1.1 Engineering challenges

Philo unit 6 was a prototype to prove supercritical technology, hence its small size at half the size of the largest unit at the time; future units were scaled up. Coincidently, Philo unit 6 was built on the former site of Philo unit 1 which was the first unit to employ single-heat (ASME, 2003a).

The superheat pressure of 31 MPa was impressive as the highest before that in the USA was 17 MPa; although Hüls unit 1 reached 30 MPa in 1956. To reach supercritical steam conditions with double-reheat, Philo unit 6 employed advanced materials; a new boiler design (or technically a steam generator, as the water does not boil with supercritical cycles); advanced water treatment (filtering, de-mineralisation and chemical treatment); high pressure water boiler feed pumps (BFP), which pumped 85 kg/s of water at 37.9 MPa; configuration of the steam bypass systems; and a new method of reliable and automated process control. Figure 7 shows a process flow diagram (PFD) of the double-reheat cycle (ASME, 2003a).

Superheated steam from the boiler first enters the high pressure (HP) module of the single shaft turbine and flows towards the front of the turbine. The steam exits the HP module and passes through a secondary heat exchanger in the boiler, known as the primary reheater, and then passes through the first stage of the intermediate pressure (IP1) turbine, again flowing towards the front. The steam exits the IP1 module and is sent through the secondary reheater in the boiler before passing through the second stage of the intermediate pressure (IP2) module, but this time flowing towards the back and exiting to a crossover pipe into the low pressure (LP) module, half flowing forwards and half flowing backward (ASME, 2003a).

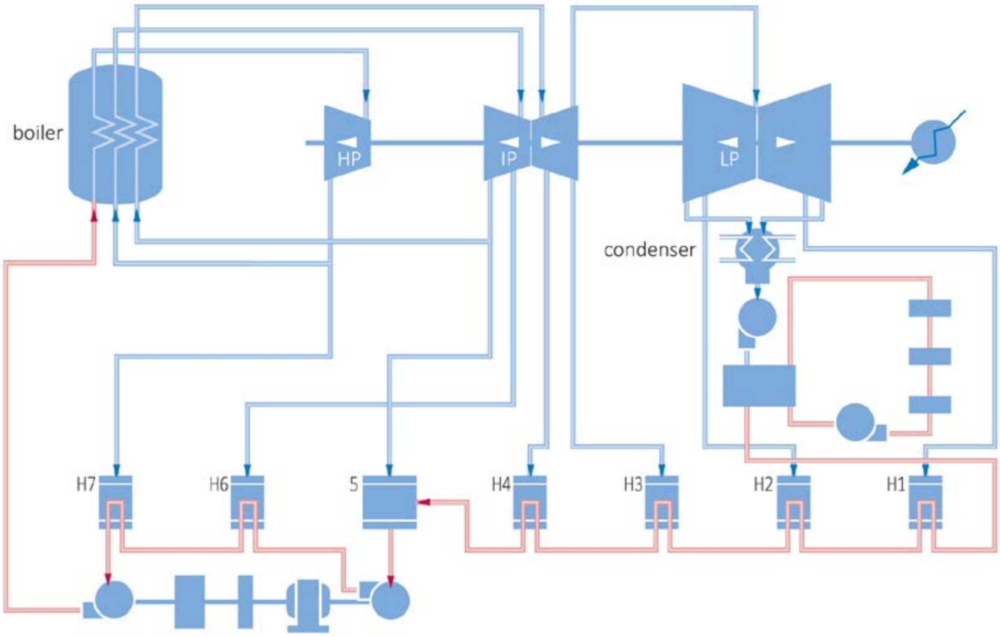

Figure 7 PFD of the world's first double-reheat cycle at Philo unit 6 (ASME, 2003a)

Interestingly, the engineers at Philo unit 6 used extrapolated measurements of steam properties (from data up to only 4.1 MPa) from 1936. The American Society of Mechanical Engineers (ASME) published up-to-date works in 1963 (ASME, 2003a).

4.1.2 Performance

After one year of operation, an engineer from Babcock & Wilcox said *"No real difficulties were encountered during the initial start-up and the few troubles which have shown up subsequently are minor compared with those which ordinarily might be expected in a major engineering development of this type"* (ASME, 2003a).

One problem was encountered when copper deposits were found in the boiler and turbine. This copper had been carried over by the water/steam from copper components. A new chemical cleaning procedure prevented further copper deposition and future supercritical steam cycle components avoided the use of copper (ASME, 2003a).

4.1.3 Historic Mechanical Engineering Landmark

On the 7th August 2003, Philo unit 6 was designated as a Historic Mechanical Engineering Landmark by the American Society of Mechanical Engineers on the 50th anniversary of its construction. Philo unit 6 pioneered engineering innovations that vastly improved power plant generating efficiency, and subsequently generated unprecedented levels of power from coal efficiently. The advanced engineering employed at Philo unit 6 has been used in other PCC plants. The ASME said that *'Breaking the critical steam barrier presented many engineering challenges analogous to those surmounted in breaking the sound barrier'* (ASME, 2003a).

4.2 Eddystone 1

Eddystone unit 1 was commissioned in 1959 in Pennsylvania. Unit 1 was owned by Philadelphia Electric Company, later PECO, and then Exelon. Eddystone 1 was designed and built by an entirely different team to those who built Philo 6. The thermodynamic calculations for Eddystone 1 were calculated with manual methods and more accurate steam properties than used in Philo 6. After Eddystone 1, computer programmes soon took over this task. Eddystone unit 1 was decommissioned in 2011, after 52 years of service (Sourcewatch, 2015).

4.2.1 Engineering

ABB Combustion Engineering manufactured the two pass boiler, which avoided the necessity for spray de-superheating and provided constant reheat temperature at most load levels.

The cross-compound turbine, manufactured by Westinghouse Electric, was rated at 325 MWe and had design ultra-supercritical (USC) steam conditions of 649°C/565°C/565°C/34.5 MPa. The 3600 rpm shaft contained the very high pressure turbine (VHP) and high pressure turbine (HP) modules and the 1800rpm shaft contained the double-flow IP module and two-single flow low pressure (LP) modules, which had 44 inch (1.12 m) last row blades.

Nine stages of feedwater preheating raised the temperature of the condensate to 293°C. There was a condensate pump and three BFP (LP, IP and HP). The LP and IP-BFP were driven by constant electrical motors, whereas the HP-BFP had a non-condensing variable speed turbine and its exhaust was used in a stage of feedwater preheating.

To maximise steam cycle efficiency, the following items were optimised: the pressure level of each water heater; the use of drain cooler and heater de-superheater zones; the location of heater drains; advanced water treatment; and the disposition of pump and turbine shaft-seal drains. The lowest pressure steam bleed was used to temper combustion air and in a low-level economiser to heat condensate, and thus lower the stack temperature to about 93°C (which was later removed due to excessive fouling). The final design heat rate was 8778 kJ/net kWh. Figure 8 shows a PFD of the double-reheat cycle at Eddystone unit 1 (ASME, 2003b).

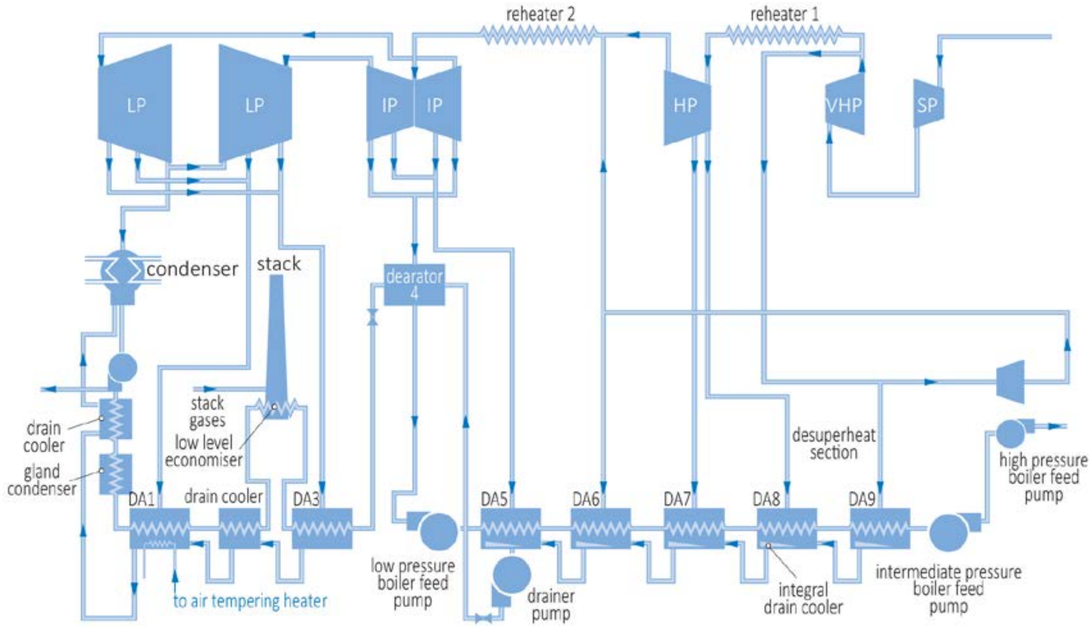

Figure 8 PFD of the double-reheat cycle at Eddystone unit 1 (ASME, 2003b)

Eddystone was one of the first PCC plants to use austenitic steels to reach such high steam conditions. The main steam piping, inner shell of the 3600 rpm turbine, the four nozzle chambers and the valve bodies for the governing and stop valves (and discharge pipes) were made of austenitic stainless steel (12–18% Cr, mostly Type 316) (ASME, 2003b).

4.2.2 Start-up

To start-up the double-reheat unit, a minimum of 30% of the design water/steam flow was required to flow through the boiler at a throttle pressure of 24 kPa (3.500 psig). The turbine was by-passed until the steam reached a certain temperature, at which point the throttle and hot-reheat inlet control valves were partially opened. The gradual increase in steam flow to the turbine occurred in conjunction with an increase in generator excitation to increase electrical output. The control valves were fully open at 260 MW and a throttle pressure of 24 MPa. This start-up procedure required advanced integrated controls which simultaneously operated the boiler, turbine and bypass systems. Load was further increased by increasing the operating pressure from 24 MPa to 34.5 MPa. This is known as sliding pressure operation; it reduces pumping power and eliminates throttling on the control valves, thus increasing electrical efficiency (ASME, 2003b).

The bypass system used at Eddystone unit 1 has since been improved. New double-reheat units use superimposing circulation, which by-pass much less steam, lose less energy and have far fewer valves, 19 compared to 152 at Eddystone unit 1. Additionally, by-passed steam can be used in the feedwater preheaters (ASME, 2003b).

4.2.3 Performance

In 1962, operating with 649°C superheated steam, the unit availability was 82.6% and its average load was 331 MW. The design heat rate was 8683 kJ/kWh (8230 Btu/kWh), however the best measured heat rate was approximately 9000 kJ/kWh (8530 Btu/kWh) (ASME, 2003b). The unit has an assumed net electrical efficiency of 39.4% (IEA CCC, 2012).

In the 1960s, several instances of rotor vibration occurred due to seal rubbing on the 3600 rpm turbine. This damage to the nested seals at the shaft ends resulted in steam leaks. A different material was used for the inner modules, as well as replacing nested seals with conventional spring backed labyrinth seals and reducing the superheat steam temperature from 649°C to 621°C. Soon after, excessive fireside corrosion of the superheater and reheater surfaces reduced the superheat steam temperature to 610°C and 33 MPa (ASME, 2003b).

In the 1970s and 1980s, performance further deteriorated with the use of lower quality coals and additional air pollution control systems. During a start-up in 1993, the VHP module overheated which caused some of the rotating blades to fail. The unit was de-rated to 230 MW until 1995 when a new 3600 rpm rotor was installed. The boiler stop valves cracked during operation; this was solved with a new valve using different materials (ASME, 2003b).

The ultra-pure feedwater caused leaching of alloying elements from the steam side of high temperature materials. Copper oxide deposits were found on the turbine blades. Further deposits were prevented with a condensate polishing filter, fitted to the end of the LP heater, and substituting copper tube heaters with ones made of steel (ASME, 2003b).

4.3 Dean H Mitchell 5 and 7

Dean H Mitchell units 5 and 7 are two hard coal-fired double-reheat units commissioned in 1959 in Indiana. ABB Combustion Engineering and General Electric manufactured the boiler and turbine respectively. The 138 MWe subcritical units have steam conditions of 541°C/341°C/541°C/12 MPa and reach 27% efficiency (Platts, 2014; IEACCC, 2012).

4.4 Breed 1

Breed unit 1 was a coal-fired double-reheat unit commissioned in 1960 and is now decommissioned. Unit 1 was owned by Indiana Michigan Power Company. Babcock & Wilcox manufactured the boiler, General Electric manufactured the turbine. The 485.6 MWe supercritical unit had the following steam conditions 565°C/565°C/565°C/24 MPa and reached 39% electrical efficiency (type CC6F26) (Platts, 2014).

4.5 Philip Sporn 5

Philip Sporn 5 was a coal-fired double-reheat unit commissioned in 1960 and decommissioned in 2010. It was owned by Appalachian Power Company. Babcock & Wilcox manufactured the boiler and General Electric manufactured the turbine (CC6F26). The 485.6 MWe supercritical unit had the following steam conditions 565°C/565°C/565°C/24.1 MPa (Sourcewatch, 2015; Platts, 2014; IEACCC, 2012).

4.6 Eddystone 2

Eddystone unit 2 was a hard coal-fired double-reheat unit commissioned in 1961 in Pennsylvania. Unit 2 was owned by Philadelphia Electric Company, later PECO, and then Exelon. ABB Combustion Engineering manufactured the boiler and General Electric manufactured the turbine. The 339 MWe supercritical unit had the following steam conditions 565°C/565°C/565°C/24.1 MPa and an electrical efficiency of 39.4% (IEACCC, 2012). Eddystone unit 2 was decommissioned in 2011 (Sourcewatch, 2015).

4.7 Tanners Creek 4

Tanners Creek unit 4 is a hard coal-fired double-reheat unit in Lawrenceburg. The unit is owned by Indiana Michigan Power and was commissioned in 1964. Babcock & Wilcox and General Electric manufactured the boiler and turbine (model CC4F38), respectively. The 580 MWe supercritical unit has steam conditions of 538°C/552°C/565°C/24 MPa and reaches an assumed net electrical efficiency of 39%. The unit will be decommissioned in 2015 (Sourcewatch, 2015; Platts, 2014; IEA CCC, 2012).

4.8 Cardinal 1 and 2

Cardinal units 1 and 2 are two hard coal-fired double-reheat units commissioned in 1964 in Brilliant (Ohio). They are owned by Cardinal Operating. Babcock & Wilcox and General Electric manufactured the boiler and turbine (model TC6F30) respectively. The two 600 MWe supercritical units have steam conditions of 538°C/551°C/567°C/26 MPa and assumed net electrical efficiencies of 39% and 38.4%, respectively (Platts, 2014; IEA CCC, 2012).

4.9 Chalk Point 1 and 2

Chalk Point units 1 and 2 are two hard coal-fired double-reheat units commissioned in 1964 in Aquascutum (Maryland). They are owned by NRG Energy. Babcock & Wilcox and General Electric manufactured the boiler and turbine (model CC4F30) respectively. The two 364 MWe supercritical units have steam conditions of 538°C/552°C/565°C/24 MPa and reach an assumed net electrical efficiency of 39% and 38.4%, respectively. Both units will be decommissioned in 2017 (Sourcewatch, 2015; Platts, 2014; IEA CCC, 2012).

4.10 Hudson 1

Hudson 1 is a gas-fired double-reheat unit commissioned in 1964 in Jersey City (New Jersey) and is owned by PSEG Fossil. Babcock & Wilcox manufactured the boiler and Westinghouse Electric manufactured the turbine (model TC4F28). The 455 MWe unit has steam conditions of 538°C/552°C/565°C/24 MPa and reaches an assumed net electrical efficiency of 38.4% (Platts, 2014; IEA CCC, 2012).

4.11 Herbert A Wagner 3

Herbert A Wagner unit 3 is a hard coal-fired double-reheat unit. Commissioned in 1966 in Baltimore (Maryland), the unit is owned by Raven Power Holdings. Babcock & Wilcox and Westinghouse Electric manufactured the boiler and turbine (model CC2F40) respectively. The 539 MWe supercritical unit has steam conditions of 538°C/538°C/538°C/24 MPa and reaches an assumed net electrical efficiency of 38.4% (Platts, 2014; IEA CCC, 2012).

4.12 Haynes 5 and 6

Haynes 5 and 6 were gas-fired double-reheat units commissioned in 1966 and 1967, respectively, and decommissioned recently. They were owned by Los Angeles Department of Water and Power. Babcock & Wilcox manufactured the boilers and General Electric manufactured the turbine (CC1F52). The 343 MWe supercritical units had the following steam conditions 552°C/565°C/565°C/14.7 MPa (Platts, 2014).

4.13 Hudson 2

Hudson 2 is a hard coal-fired double-reheat unit commissioned in 1968 in Jersey City (New Jersey) and is owned by PSEG Fossil. Foster Wheeler manufactured the boiler and Westinghouse Electric manufactured the turbine (model TC6F28). The 623 MWe unit has steam conditions of 538°C/552°C/565°C/24 MPa and reaches an assumed net electrical efficiency of 38.4% (Platts, 2014; IEA CCC, 2012).

4.14 Muskingum River 5

Muskingum River unit 5 is a hard coal-fired double-reheat unit commissioned in 1968 in Beverly (Ohio). The unit is owned by AEP Generation Resources. Babcock & Wilcox and General Electric manufactured the boiler and turbine (model TC6F30) respectively. The 615 MWe supercritical unit has steam conditions of 538°C/552°C/565°C/24 MPa and reaches an assumed net electrical efficiency of 38.4% (Platts, 2014; IEA CCC, 2012). Unit 5 will stop firing coal in 2015 (Sourcewatch, 2015).

4.15 Canal 1

Canal 1 is an oil-fired double-reheat unit owned by NRG Energy. Commissioned in 1968, it is rated 585 MWe and has steam conditions of 538°C/538°C/538°C/24.1 MPa. Babcock & Wilcox manufactured the boiler and Westinghouse Electric manufactured the turbine (TC4F31) and generator (Platts, 2014).

4.16 Big Sandy 2

Big Sandy unit 2 is a hard coal-fired double-reheat unit. Commissioned in 1969 in Kentucky, the unit is owned by Kentucky Power. Foster Wheeler and General Electric manufactured the boiler and turbine (model TC4F33.5) respectively. The 816 MWe supercritical unit has steam conditions 538°C/552°C/565°C/24 MPa and reaches an assumed net electrical efficiency of 38.4% (Platts, 2014; IEA CCC, 2012). The unit will stop burning coal in 2015 (Sourcewatch, 2015).

Up until 1969, cross-compound turbines were used in double-reheat units. This was because thermal expansion limited the number of modules on tandem compound turbines. By 1969, a tandem-compound double-reheat turbine was commissioned. This turbine combined the HP module (538°C and 24.1 MPa) and the primary reheat IP1 module (552°C) in a single opposed flow casing. The secondary reheat IP2 module (552°C) had a double-flow arrangement and there were three double-flow LP modules. The design was successful and provided excellent reliability and performance (MPS, 1999).

4.17 Brayton Point 3

Brayton Point unit 3 is a hard coal-fired double-reheat unit commissioned in 1969 in Massachusetts. The unit is owned by Energy Capital Partners. Babcock & Wilcox and Westinghouse Electric manufactured the boiler and turbine (model TC6F28) respectively. The 643 MWe supercritical unit has steam conditions of 538°C/552°C/565°C/24 MPa and an assumed net electrical efficiency of 31.4% (Platts, 2014; IEA CCC, 2012). Unit 3 will be decommissioned as of May 2017 (Sourcewatch, 2015).

4.18 Four Corners 4 and 5

Four Corners units 4 and 5 are two hard coal-fired double-reheat units in Fruitland (Idaho). They were commissioned in 1969 and 1970, respectively. They are owned by Arizona Public Services. Babcock & Wilcox and General Electric manufactured the boilers and turbines (model CC2F52) respectively. The 818 MWe supercritical units have steam conditions of 538°C/538°C/540°C/26 MPa. Unit 4 reaches 32% efficiency and unit 5 reaches an assumed net electrical efficiency of 33% (Platts, 2014; IEA CCC, 2012).

4.19 Genoa 1

Genoa unit 1 is a hard coal-fired double-reheat unit in Genoa (Wisconsin). Commissioned in 1969, the unit is owned by Dairyland Power. ABB Combustion Engineering and Westinghouse Electric manufactured the boiler and turbine (model TC4F28) respectively. The 379 MWe supercritical unit has steam conditions of 538°C/538°C/538°C/24 MPa and reaches an assumed net electrical efficiency of 31.05% (Platts, 2014; IEA CCC, 2012).

4.20 Marshall 3 and 4

Marshall units 3 and 4 are two hard coal-fired double-reheat units in Terrell (North Carolina), commissioned in 1969 and 1971 respectively. They are both owned by Duke Energy Carolinas. ABB Combustion Engineering and General Electric manufactured the boiler and turbine (model TC4F33.5) respectively. The 650 MWe supercritical units have steam conditions of 538°C/538°C/538°C/24 MPa. Unit 3 reaches 31.65% and unit 4 reaches an assumed net electrical efficiency of 32.65% (Platts, 2014; IEA CCC, 2012).

4.21 Mitchell 1 and 2

Mitchell units 1 and 2 are two hard coal-fired double-reheat units in Moundsville (West Virginia), commissioned in 1971. They are both owned by Ohio Power. Foster Wheeler and Westinghouse Electric manufactured the boiler and turbine (model TC4F33.5) respectively. The 800 MWe units have steam conditions of 538°C/552°C/565°C/24 MPa and reach an assumed net electrical efficiency of 39.4% (Platts, 2014; IEA CCC, 2012).

4.22 John E Amos 1 and 2

John E Amos units 1 and 2 were commissioned in 1971 and 1972 respectively, in Saint Albans (West Virginia). They are both owned by Appalachian Power. Foster Wheeler and General Electric manufactured the boiler and turbine (model TC4F33.5) respectively. The 816.3 MWe units have steam conditions of 538°C/552°C/565°C/24 MPa and reach an assumed net electrical efficiency of 39.4% (Platts, 2014; IEA CCC, 2012).

4.23 Gibbons Creek 1

Gibbons Creek double-reheat unit 1 was commissioned in 1982 in Carlos (Texas). The unit fires lignite coal and is owned by Texas Muni Power Agency. ABB Combustion Engineering and General Electric manufactured the lignite-fired boiler and turbine (model TC2F33.5), respectively. The 480 MWe unit has steam conditions of 538°C/538°C/540°C/16.5 MPa and reaches an assumed net electrical efficiency of 33% (Platts, 2014; IEA CCC, 2012).

4.24 Hugo 1

Hugo double-reheat unit 1 was commissioned in 1982. Babcock & Wilcox and Westinghouse Electric manufactured the boiler and turbine respectively. The 418 MWe unit has steam conditions of 542°C/542°C/343°C/17 MPa and reaches an assumed net electrical efficiency of 33% (IEA CCC, 2012).

4.25 Analysis

From the late 1940s to the mid-1980s, the total capacity of PCC plant in the USA increased from a few GWe to around 300 GWe. Power plant designers calculated that the more fuel efficient supercritical double-reheat units were more economical over the plant lifetime than subcritical boilers – such units started coming online in the late 1950s. From the 1950s to the 1970s, the market for PCC technology was dominated by North American companies, such as Babcock & Wilcox and General Electric (Yeh and Rubin, 2007).

Table 2 lists the double-reheat units built in the USA, with details of year commissioned, primary fuel, size (MWe), steam conditions (°C/°C/°C/MPa) and electrical efficiency (%) (most of which are assumed values), in chronological order of year commissioned.

Table 2 List of double-reheat units in the USA

Unit	Commissioned	Primary Fuel	Size (MWe)	Steam Conditions (°C/°C/°C/MPa)	Electrical Efficiency (%)
Philo 6	1957	Hard coal	120	621/565/538/31	40
Eddystone 1	1959	Hard coal	325	649/565/565/34.5, later 610/565/565/33	39.4
Dean H Mitchell 5	1959	Hard coal	138	541/341/541/12	27
Dean H Mitchell 7	1959	Hard coal	138	541/341/541/12	27
Breed 1	1960	Hard coal	486	565/565/565/24	39
Philip Sporn 5	1960	Hard coal	486	565/565/565/24	
Eddystone 2	1961	Hard coal	339	565/565/565/24	39.4
Hudson 1	1964	Gas	455	538/552/565/24	38.4
Tanner Creek 4	1964	Hard coal	580	538/552/565/24	39
Cardinal 1	1964	Hard coal	600	538/551/567/26	39
Cardinal 2	1964	Hard coal	600	538/551/567/26	38.4
Chalk Point 1	1964	Hard coal	364	538/552/565/24	39
Chalk Point 2	1964	Hard coal	364	538/552/565/24	38.4
Herbert A Wagner 3	1966	Hard coal	539	538/538/538/24	38.4
Haynes 6	1967	Gas	343	552/565/565/14.7	
Hudson 2	1968	Hard coal	623	538/552/565/24	38.4
Muskingum River 5	1968	Hard coal	615	538/552/565/24	38.4
Canal 1	1968	Oil	585	538/538/538/24.1	
Haynes 5	1969	Gas	343	552/565/565/14.7	
Brayton Point 3	1969	Hard coal	643	538/552/565/24	31.4
Big Sandy 2	1969	Hard coal	816	538/552/565/24	38.4
Four Corners 4	1969	Hard coal	818	538/538/540/26	32
Four Corners 5	1969	Hard coal	818	538/538/540/26	33
Genoa 1	1969	Hard coal	379	538/538/538/24	31.05
Marshall 3	1969	Hard coal	650	538/538/538/24	31.65
Marshall 4	1971	Hard coal	650	538/538/538/24	32.65
Mitchell 1	1971	Hard coal	800	538/552/565/24	39.4
Mitchell 2	1971	Hard coal	800	538/552/565/24	39.4
John E Amos 1	1971	Hard coal	816.3	538/552/565/24	39.4
John E Amos 2	1972	Hard coal	816.3	538/552/565/24	39.4
Hugo 1	1982	Hard coal	418	542/542/343/17	33
Gibbons Creek 1	1982	Lignite	480	538/538/540/16.5	33

In the 25 years from 1957 to 1982, 32 double-reheat units were commissioned in the USA amounting to approximately 17 GWe. Of these units, 27 are hard coal-fired, three are gas-fired, and there is one oil-fired and one lignite-fired unit. Babcock & Wilcox manufactured 18 boilers, Foster Wheeler manufactured six boilers and ABB Combustion Engineering manufactured eight boilers. Westinghouse Electric manufactured ten turbines and General Electric manufactured 22 turbines (Platts, 2014; IEA CCC, 2012).

For the hard coal-fired, supercritical units the steam conditions, listed in Table 2, varied greatly. This was due to inexperience with the use of austenitic steels at supercritical steam conditions. The superheat steam conditions were initially set high at 649°C and 34.5 MPa for Eddystone 1 and 621°C and 31 MPa for Philo 6. Eddystone 1 had to de-rate its superheat steam to 610°C and 33 MPa due to problems with rotor vibration and fireside corrosion. The next three units commissioned in 1960 and 1961 had superheat steam at 565°C and 24 MPa. Further problems with austenitic materials were encountered in the 1960s and early 1970s. Problems included creep and fatigue cracking of austenitic steel boiler tubes and extensive steamside oxidation caused severe wear in the boiler tubes and the turbine nozzle. As a result, the availability of these plants dropped and the maintenance costs increased significantly. Such problems were entirely due to moving to ultra-supercritical (USC) steam conditions with early austenitic materials, and nothing to do with the number of reheaters in the steam cycle. The only solution to these problems, at the time, was to de-rate the boiler and lower the steam conditions (Yeh and Rubin, 2007). The next eighteen units had superheat steam at 538°C and 24 MPa, except for three units which had a higher superheat pressure of 26 MPa. For all units the primary and secondary reheat temperatures were in the range 538–565°C (Platts, 2014; IEA CCC, 2012).

As the number of double-reheat units in the USA increased, the cost of building such units dropped from 170 $/kW to 100 $/kW in the mid-1960s, and the reliability increased. However, in the 1970s the cost of building PCC plant increased, largely because of the requirements for air pollution control and cooling towers (ASME, 2003a). Weitzel (2012) says that the double-reheat cycle with the early supercritical units in the USA increased efficiency by 1.5–2% points above single-reheat units.

Figure 9 shows a graph of the electrical efficiency and unit size with year commissioned for double-reheat units on the USA. This graph shows the increase in unit size with year commissioned, from 120 MWe to 816.3 MWe. The electrical efficiency ranged from 27% to 40%. The graph shows that the efficiency decreases slightly with time, but this is because the trend is skewed by the small and inefficient units of subcritical Hugo 1 and lignite-fired Gibbons Creek 1 (Platts, 2014; IEA CCC, 2012).

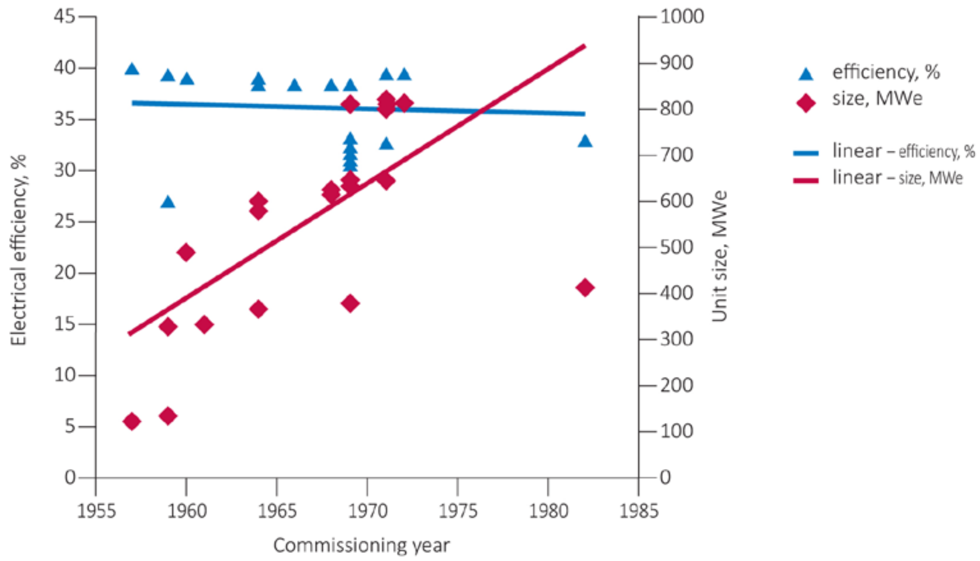

Figure 9 Efficiency and unit size of the double-reheat units in the USA (Platts, 2014; IEA CCC, 2012)

Since the 1970s, until recently, no supercritical coal-fired units were built in the USA because of a decreased electricity demand and an increasingly privatised electricity industry. One supercritical unit was commissioned in the USA in 2007 (Yeh and Rubin, 2007). Since operating at reasonable steam conditions 538°C/538–565°C/538–565°C/24 MPa for austenitic steels, the operational record of the double-reheat units in the USA has been excellent with operating lifetime greater than 50 years (Kjaer and Drinhaus, 2010a).

Interestingly, in the 1980s the Electric Power Research Institute (EPRI) in the USA investigated double-reheat turbines to operate at supercritical steam conditions of 593°C/593°C/593°C/31 MPa. However, no such plants have been built in the USA. This has been attributed to the privatisation of power plants, not favouring long-term investments (MPS, 2002; MPS, 1999).

Eleven of the 27 double-reheat units have been decommissioned, or will be soon (Sourcewatch, 2015). Some units will switch to firing gas or biomass due to more stringent emission regulations set by the Environmental Protection Agency, an abundance of low cost shale gas and a decreased electricity demand.

5 Status of double-reheat units in Italy

Chapter 5 reviews the technical and economic performance of operational and decommissioned double-reheat units in Italy.

5.1 La Spezia 3

La Spezia unit 3 in Italy was a supercritical 600 MWe natural gas-fired double-reheat unit commissioned in 1967 and recently decommissioned. It was owned by ENEL. Franco Tosi Industriale manufactured the turbine (CC4F33) and Babcock & Wilcox manufactured the boiler. The unit has a steam flow of 517 t/h with the following steam conditions 542°C/552°C/566°C/24.6 MPa. The unit reaches 38.4% electrical efficiency (Platts, 2014; IEA CCC, 2012).

5.2 La Spezia 4

La Spezia unit 4 in Italy is a supercritical 600 MWe bituminous coal-fired double-reheat unit commissioned in 1968 in Italy. It is owned by ENEL. Franco Tosi Industriale manufactured the turbine (CC4F33) and Babcock & Wilcox manufactured the boiler. The unit has a steam flow of 517 t/h with the following steam conditions 542°C/552°C/566°C/24.6 MPa and reaches an assumed net electrical efficiency of 38.4% (Platts, 2014; IEA CCC, 2012).

5.3 Analysis

Only two double-reheat units were built in Italy, one coal and one gas-fired, in the last 60s. Franco Tosi Industriale manufactured the double-reheat turbines in Italy, whereas Babcock & Wilcox manufactured both boilers.

6 Status of double-reheat units in Japan

Chapter 6 reviews and analyses the technical and economic performance of operational and decommissioned double-reheat units in Japan.

6.1 Himeji Daini 4

Himeji Daini 4 was a liquefied natural gas-fired double-reheat owned by Kansai Electric Power. The unit was commissioned in 1968 and is now decommissioned. ABB Combustion Engineering manufactured the boiler and Westinghouse Electric manufactured the turbine (type TC4F28.5). The 450 MWe supercritical unit had 333 t/h of steam flow with the following steam conditions 538°C/552°C/556°C/24.1 MPa (Platts, 2014).

6.2 Kainan 1 and 2

Kainan units 1 and 2 are two oil-fired double-reheat units in Japan owned by Kansai Electric Power. Commissioned in 1970, the units are rated 450 MWe each and have steam conditions of 538°C/552°C/566°C/24.1 MPa. Babcock-Hitachi manufactured the boilers and Toshiba manufactured the turbines and generators (Platts, 2014).

6.3 Takasago Kansai 1 and 2

Takasago Kansai units 1 and 2 were two oil-fired double-reheat units owned by Kansai Electric Power. The units were commissioned in 1971 and are both now decommissioned. Mitsubishi Heavy Industries manufactured the boilers and turbines (type TC4F28.5). The 450 MWe supercritical units had 348 t/h of steam flow with the following steam conditions 538°C/552°C/556°C/24.1 MPa (Platts, 2014).

6.4 Himeji Daini 5 and 6

Himeji Daini units 5 and 6 are two liquefied natural gas-fired double-reheat units owned by Kansai Electric Power. The unit was commissioned in 1973. Mitsubishi Heavy Industries manufactured the boiler and turbine (type TC4F31) for unit 5. Ishikawajima-Harima Heavy Industries manufactured the boiler and Hitachi manufactured the turbine (type TC4F33.5) for unit 6. The 600 MWe supercritical units had 449 t/h of steam flow with the following steam conditions 538°C/552°C/556°C/24.1 MPa (Platts, 2014).

6.5 Kainan 3 and 4

Kainan units 3 and 4 are two oil-fired double-reheat units in Japan owned by Kansai Electric Power. Commissioned in 1974 and 1973, respectively, the supercritical units are rated 600 MWe each, have a maximum steam flow rate of 466 t/h and steam conditions of 538°C/552°C/566°C/24.1 MPa. For unit 3, Mitsubishi Heavy Industries manufactured the boiler and turbine (TC4F31); Melco manufactured the generator. For unit 4, Babcock-Hitachi manufactured the boiler and Toshiba manufactured the turbine (TC4F30) and generator (Platts, 2014).

6.6 Tanagawa Daini 1 and 2

Tanagawa Daini units 1 and 2 were two 600 MWe oil-fired double-reheat units operated by the Kansai Power Company. They are now decommissioned (Yamauchi, 2015).

6.7 Kawagoe 1 and 2

Kawagoe units 1 and 2 are two liquefied natural gas-fired double-reheat units in Japan owned by Chubu Electric Power. Commissioned in 1989 and 1990, respectively, the supercritical units are rated 700 MWe each, have a maximum steam flow rate of 542 t/h and steam conditions of 565°C/565°C/565°C/31 MPa. Mitsubishi Heavy Industries manufactured the boilers and Toshiba manufactured the tandem-compound turbine-generators (model TC4F31). The units have sliding pressure operation (Platts, 2014).

The tandem-compound turbine was chosen over a cross-compound type due to a commercial compromise. The cross-compound turbine would have conferred an additional 0.6% points in net electrical efficiency (LHV). Kawagoe unit 1 is designed for load following operation, which involves daily start-up/shut-down and rapid reaction to changing demand. Kawagoe unit 1 reaches 45% net electrical efficiency (LHV). At full-load the unit has a net electrical efficiency of 46.8% (LHV) with an auxiliary load of 2.8% points. The design engineers estimated that if the unit was coal fired the full-load efficiency would be 44.9% (LHV), due to the auxiliary loads of coal delivery and pulverisation, and flue gas denitrification and desulphurisation (Iwanaga and others, 1990; Ishiki and others, 1990).

6.8 Analysis

Table 3 lists the thirteen oil- and gas-fired double-reheat units built in Japan, with details of year commissioned, primary fuel, size (MWe), steam conditions (°C/°C/°C/MPa) and electrical efficiency (%)(most of which are assumed values), in chronological order of year commissioned.

Table 3 List of double-reheat units in Japan

Unit	Commissioned	Primary Fuel	Size (MWe)	Steam Conditions (°C/°C/°C/MPa)	Efficiency (%)
Himeji Daini 4	1968	Gas	450	538/552/556/24.1	
Kainan 1	1970	Oil	450	538/552/566/24.1	
Kainan 2	1970	Oil	450	538/552/566/24.1	
Takasago Kansai 1	1971	Oil	450	538/552/556/24.1	
Takasago Kansai 2	1971	Oil	450	538/552/556/24.1	
Kainan 3	1973	Oil	600	538/552/566/24.1	
Himeji Daini 5	1973	Gas	600	538/552/556/24.1	
Himeji Daini 6	1973	Gas	600	538/552/556/24.1	
Kainan 4	1974	Oil	600	538/552/566/24.1	
Tanagawa Daini 1		Oil	600		
Tanagawa Daini 2		Oil	600		
Kawagoe 1	1989	Gas	700	565/565/565/31	45
Kawagoe 2	1990	Gas	700	565/565/565/31	45

Of the eleven double-reheat units, amounting to 7.2 GWe, built in Japan between 1968 and 1990, five are gas-fired and six are oil-fired. Interestingly, the first double-reheat unit in Japan commissioned in 1968 used a boiler manufactured by ABB Combustion Engineering and turbine from Westinghouse Electric, which shows the dominance of the North American companies at the time. Mitsubishi Heavy Industries manufactured six boilers and four turbines. Babcock-Hitachi manufactured three boilers and Ishikawajima-Harima Heavy Industries manufactured one boiler. Toshiba manufactured five turbines and Hitachi manufactured one turbine.

The steam conditions began modestly, compared to practice in the USA. As shown on Table 3, the first nine units operated at 538°C/552°C/556–566°C/24.1 MPa, and Kawagoe units 1 and 2 increased the steam parameters to 565°C/565°C/565°C/31 MPa. Figure 10 shows a graph of the electrical efficiency and unit size with year commissioned for double-reheat units in Japan. Unit size gradually increased from 450 to 700 MWe (Platts, 2014; IEA CCC, 2012).

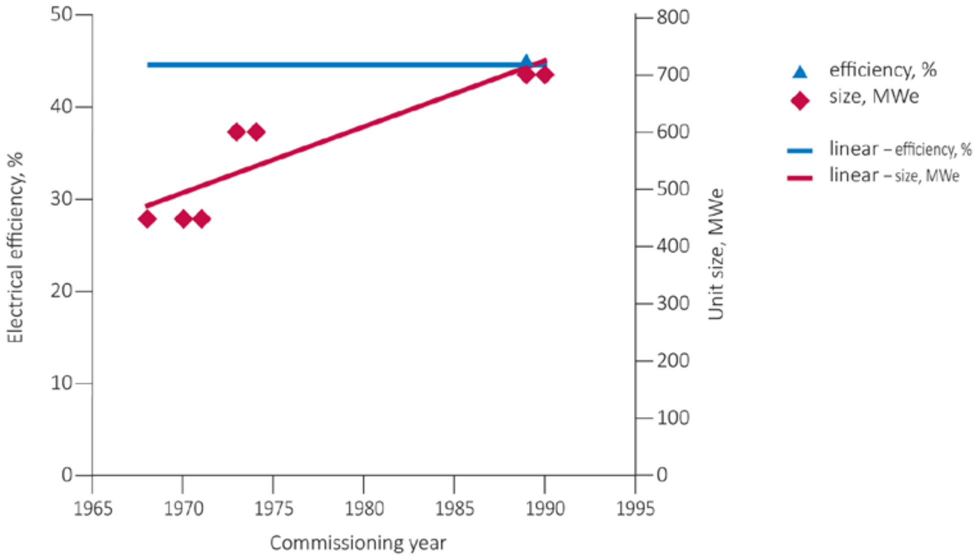

Figure 10 Efficiency and unit size of hard coal-fired double-reheat units in Japan (Platts, 2014; IEA CCC, 2012)

The gas-fired units at Kawagoe could reach an impressive net electrical efficiency of 46.8% (LHV) and be operated in load-following mode. However, firing gas in boilers is now redundant as combined cycle gas turbines (CCGT) can reach net electrical efficiencies of 60% (LHV).

Coal-fired double-reheat units have not been built in Japan because they have not been economically favourable. The cost of electricity has been lower from oil- and gas-fired double-reheat units and coal-fired single-reheat units (Yamauchi, 2015).

For turbines rated over 900 MWe spinning at 3600 rpm and power grids operating at 60 Hz, such as those in Japan, a tandem-compound arrangement would cause excessively high centrifugal forces on the last stages of the LP turbine blades. The solution was to have a cross-compound arrangement, with the LP modules on a secondary low-speed (1800 rpm) train. Titanium based alloys now allow last stage LP module blades to spin at 3600 rpm, with larger annular exit areas, which allow tandem-compound arrangement (MPS, 2010).

7 Status of double-reheat units in Denmark

Chapter 7 reviews and analyses the technical and economic performance of the operational double-reheat units in Denmark.

7.1 Skærbæk 3

In Denmark, Skærbæk unit 3 is a natural gas-fired double-reheat unit commissioned in 1997. It can also fire light fuel oil (LFO). This unit generates 392 MWe of power and 447 MWth for a district heating system, making the unit 93% energy efficient. At the time of commissioning, Skærbæk unit 3 set the world record for natural gas-fired plants with a total efficiency of 49% in 100% power generation mode (Dong Energy, 2015). The boiler was manufactured by Burmeister & Wain Energy A/S and GEC-Alstom manufactured the turbine. The unit has a steam flow of 972 t/h and steam conditions of 580°C/580°C/580°C/29 MPa (Poulsen and Bendixen, 2006).

7.2 Nordjylland 3

Nordjylland unit 3, rated 415 MWe, was commissioned in Northern Jutland, close to Aalborg, in Denmark in 1998. The decision to build unit 3 was made in 1992, making the design plus construction time six years (MPS, 1998).

7.2.1 Boiler

FLS miljø and Burmeister & Wain Energi designed the boiler shown in Figure 11. Aalborg Industries, Burmeister & Wain Energi (BWE) and Vølund Energy constructed the boiler. Internationally-traded bituminous coals (25.2 MJ/kg LHV or 26.4 MJ/kg HHV) are fired normally, but the unit can also fire heavy fuel oil (HFO). The boiler is a once-through USC Benson tower boiler (12.25 m^2 by 70 m) with tangential corner firing; with a spiral wound evaporator, sliding pressure operation and double reheaters. The 16 BWE 4 attached flame (AF) burners can fire coal and oil. Staged combustion is employed to lower NOx emissions. The over burner air (OBA) system and the flue gas recirculation (FGR) together control the reheater outlet temperatures. A screen and the first stage of the superheater are used to protect the HP and reheater 1 final superheaters from the combustion chamber (MPS, 1998).

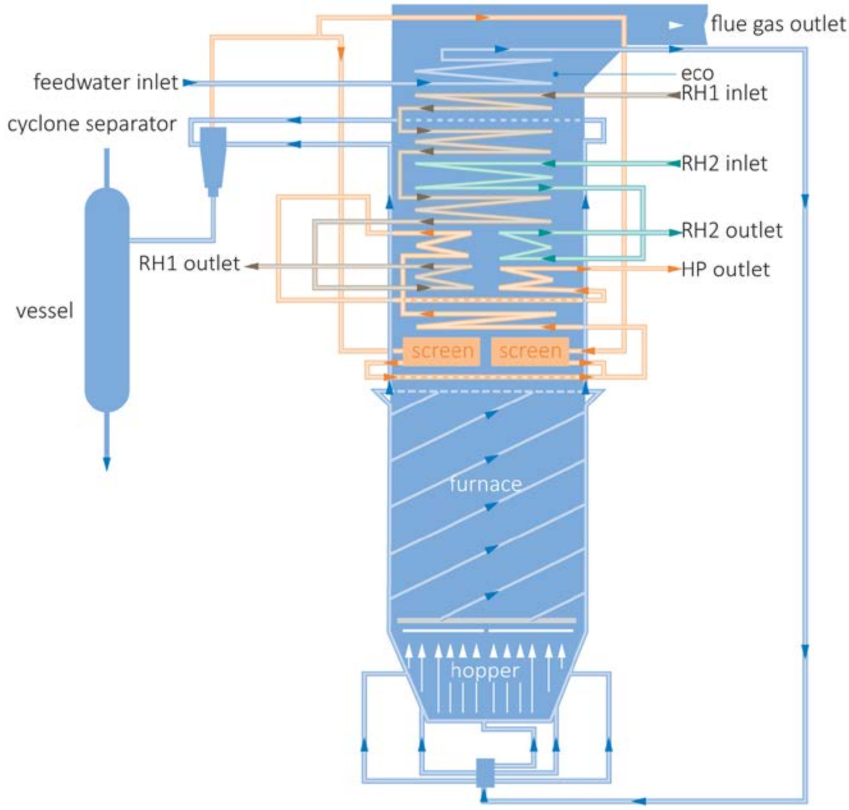

Figure 11 Cross-section of boiler at Nordjylland PCC plant unit 3 (Jensen, 2000)

7.2.2 Turbine

The tandem-compound, double-reheat impulse turbine, was manufactured by GEC-Alstom. The turbine has the following steam conditions, 582°C/580°C/580°C/29 MPa, with a steam flow of 972 t/h. The generator generates 415 MWe at 3000 rpm (Poulsen and Bendixen, 2006). The turbine is made up of a single-flow VHP; a combined HP (7.4 MPa) and IP0 (1.9 MPa) modules in opposed flow arrangement; a double-flow IP1/2 (0.7 MPa) module; and two asymmetrical double-flow LP modules, with 860 mm last row blades. Each of the VHP, HP and IP steam inlets are controlled by two stop and control valve assemblies (combined in same valve chest) (Kjaer, 2003; MPS, 1998).

The unit can run in two modes, power only mode and combined heat and power (CHP) mode, which heats a district heating system. Ten steam bleeds are taken from the turbine, at various pressures, for the condensate/feedwater preheating. The feedwater can be preheated to 300°C. This includes two steam bleeds (A3/H1 and A4/H2), on the double-flow IP module, to serve the condensing heat exchangers for the district heating grid. The condensate is pumped through seven stages of low pressure feedwater heaters to the de-aerator unit, which converts the condensate to feedwater and acts as an eighth low pressure heater. From the de-aerator, the two variable speed electric boiler feed pumps (BFP) force the feedwater through two high pressure feedwater heaters and one feedwater de-superheater, which are heated with steam originating from two bleeds. Feedwater preheaters are characterised by condensing the steam whereas feedwater de-superheaters are characterised by cooling the steam. The turbine has sliding pressure operation to optimise efficiency at low loads, to a minimum output of 20% (IEA, 2007;

Kjaer, 1993). Due to high amounts of intermittent power generation from renewable energy on the Danish grid, Nordjylland unit 3 cycles from 20% load to base load on a daily basis.

There is heat recovery on the components, such as fans and pumps, which heat the building, combustion air and provide the initial stage of condensate preheating (MPS, 1998). Figure 12 shows a PFD of the double-reheat steam cycle at Nordjylland unit 3 (Kjaer, 2003; MPS, 1998).

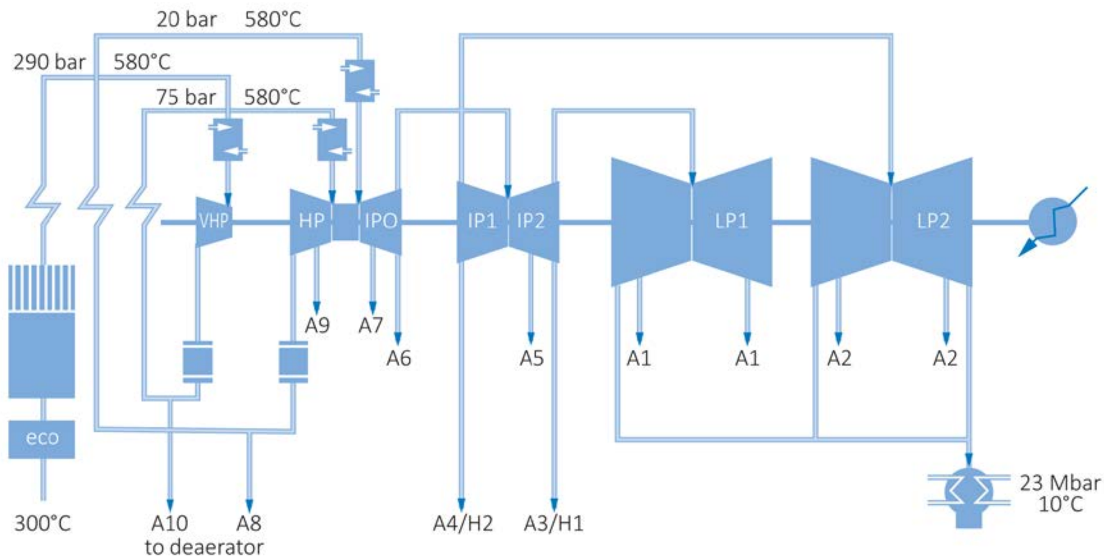

Figure 12 PFD of the double-reheat steam cycle at Nordjylland unit 3 (IEA, 2007; Kjaer, 2003)

7.2.3 High temperature materials

New materials allowed a significant increase in superheat steam conditions to 582°C and 29 MPa. Austenitic steel HTP347FG (SA213-TP347H) was used for the final superheater and martensitic steel P91 (X10CrMoVNb9-1) was used for the high pressure headers and pipework. The small unit size and the use of double-reheat cycle reduced the steam flow by 10%, which kept the size of the pressure parts small enough to manufacture. Flue gas recirculation, advanced water treatment and soot blowers were used to ensure the T11 water wall tubes did not overheat (IEA, 2007; MPS, 1998).

7.2.4 Sea-water cooling

The coastal area of Denmark has access to the North Sea, which can provide sea water cooling at an average of 10°C, reaching a minimum of 0°C, which creates an average condenser pressure of just 2.3 kPa (IEA, 2007). A low condenser pressure causes a high volumetric flow in the LP module, which increases power generation and thus efficiency. Figure 13 shows the relationship between net electrical efficiency (%, LHV), for steam conditions at 580°C/580°C/580°C/28.5 MPa, with increasing condenser pressure, when moving from sea water cooling to wet cooling towers and finally dry cooling tower (Kjaer, 1993). This figure shows that sea water cooling increases net electrical efficiency (LHV) by 1% compared to wet cooling towers.

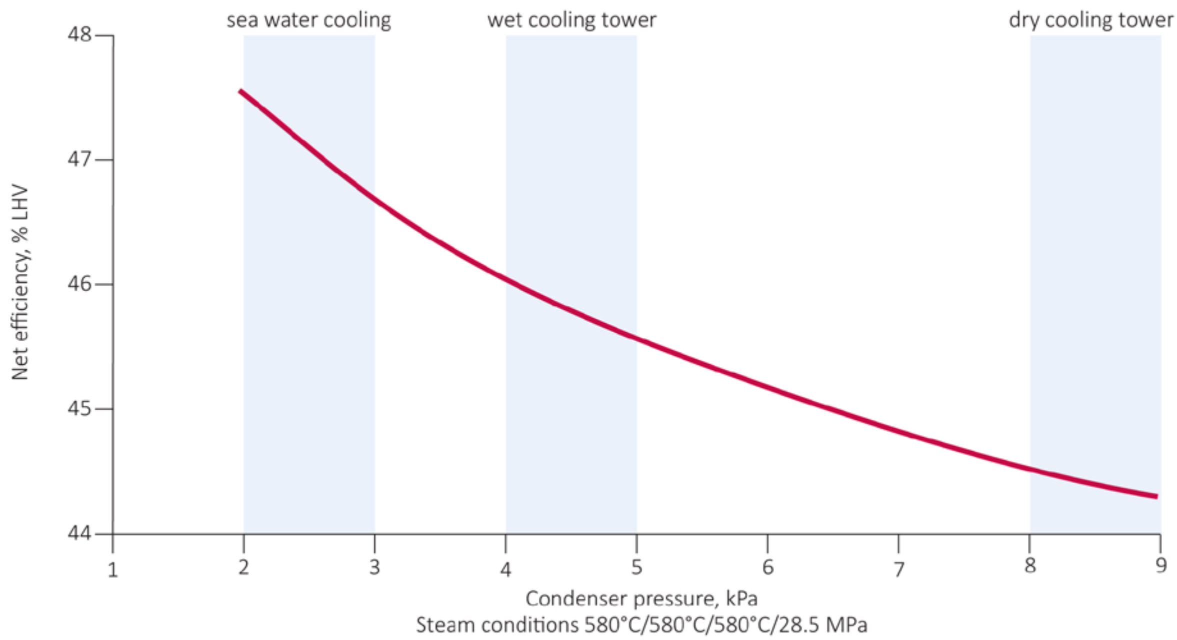

Figure 13 Impact of condenser pressure on net efficiency (Kjaer, 1993)

7.2.5 LP blade erosion

Some single-reheat cycles have low condenser pressures which give rise to relatively high moisture concentrations (wetness) in the low pressure turbine. This moisture can cause serious erosive damage, particularly to the LP turbine blades. Low condenser pressures can be found with low temperature cooling air or sea-water cooling, superheated steam temperature above 605°C and units with optimised cold ends (serial condensers or cooling towers with optimised design) (Drinhaus, 2015).

However, double-reheating increases the exhaust steam enthalpy, which reduces the steam wetness in the LP exhaust and results in less erosion in the LP turbine. Double-reheat was found to give a maximum exhaust moisture content of 8%, compared with 15% for the single-reheat, found during the cold winter. LP blade erosion has not been a problem at Nordjylland unit 3 (Kjaer, 1993; IEA, 2007; Morrison, 2011). Additionally, as the moisture content is so low, the steam extracted for feedwater preheating can be increased to an optimum level without causing LP blade erosion (Kjaer and Drinhaus, 2010).

7.2.6 Technical performance

Nordjylland unit 3 reaches 47% net electrical efficiency (LHV) in power only mode, and is currently (Dec 2014) the world's most efficient PCC unit (Morrison, 2011; Poulsen and Bendixen, 2006; Vattenfall, 2014). The combination of low temperature sea water cooling (10°C), high superheat steam (580°C) and double-reheat substantially reduce losses to the Carnotisation Gap in the Rankine cycle used in PCC plants, making the cycle more thermodynamically efficient (Poulsen and Bendixen, 2006). Compared to Esjberg unit 3, a single-reheat supercritical PCC plant in Denmark operating with superheat steam at 560°C and 25 MPa, Nordjylland unit 3 increases net electrical efficiency by 1% point by going to ultra-supercritical (USC) conditions and by 0.9% point by having double-reheat as opposed to single-reheat (Kjaer, 1990). In 2005, Nordjylland unit 3 achieved the performance results, shown in Table 4, for power only mode and combined heat and power (CHP) mode (Poulsen and Bendixen, 2006).

Table 4 Performance data from Nordjylland unit 3 (Poulsen and Bendixen, 2006)

Performance aspect	Power only mode (100% load, condensing mode with 10°C cooling water)	Combined heat and power mode (100% load, back pressure mode, 4°C cooling water)
Availability	98%	98%
Generator output	411 MWe	339.5 MWe
Auxiliary power consumption, total	26 MWe	26.5 MWe
Auxiliary power consumption of denitrification and desulphurisation systems	3 MWe	3 MWe
Electrical output to grid (400 kV)	385 MWe	313 MWe
District heating output	0 MJ/s	422 MJ/s
Turbo generator heat rate (based on generator output)	6736.6 kJ/kWh	8150.3 KJ/kWh
Boiler efficiency	94.2%	94.2%
Power plant heat rate (based on generator output)	7151.4 kJ/kWh	8652.1 kJ/kWh
Gross calorific value of coal	26 MJ/kg	26 MJ/kg
Specific coal consumption (based on generator output)	275 g/kWh	148 g/kWh
Specific coal consumption (400 kV to grid)	293 g/kWh	154 g/kWh
Thermal efficiency (400 kV to grid)	47.2 %	90%
Emissions	Regulations met	Regulations met

At 415 MWe, almost half that of the largest German and Japanese units at the time, such high efficiency demonstrates that increasing unit size is not necessarily accompanied by increased electrical efficiency. However, around 400 MWe is about the smallest worthwhile size to gain high efficiency with a USC unit (Henderson, 2015).

7.2.7 Industrial symbiosis

Nordjylland PCC plant is part of the industrial symbiosis network in Denmark. The bottom ash, fly ash and gypsum from the units are sold to the construction industry, and the waste heat is used in a district heating scheme – there is minimal waste. This symbiosis minimises environmental damage and lowers costs.

7.2.8 Process economics

At the time, the double-reheat option cost DM 20 million more than the single-reheat option. Assuming an imported coal price of 73 $/t, the cost benefit of the secondary reheat loop was said to be 'in the lower region of the break-even price' (Kjaer, 1993).

Initially, ELSAM owned the Nordjylland unit 3. Since then, DONG Energy bought ELSAM. DONG Energy said that the contracting strategy was owner design with multi-contract procurement. Vattenfall have now bought the plant from DONG Energy. In 2007, the IEA were unable to obtain economic information from the plant operators due to commercial sensitivity. Siemens said that a similar 800 MWe USC unit would cost around 1500 US$/kW, which excludes owner's costs and interest during construction (IDC). In 2007, Nordjylland unit 3 had been economically worthwhile, especially as coal prices had increased and a price was developed for carbon dioxide (IEA, 2007).

7.3 Analysis

In Denmark, there is high public pressure and strong governmental demands for environmentally friendly heat and power generation. Denmark has low indigenous fossil fuel reserves and is a net energy importer. Uncertainties regarding the cost and security of natural gas supplies led Denmark to focus on coal and biomass. After extensive investigation into coal and biomass conversion technologies, the technology employed at Nordjylland unit 3 was calculated to have the highest efficiency and lowest lifecycle cost (MPS, 1999). The technology choice here is site specific. The availability of low temperature sea water cooling favours the double-reheat steam Rankine cycle, in terms of higher efficiency and low erosion. Nordjylland unit 3 is currently (March 2015) the most efficient and one of the cleanest PCC plants in the world.

Drinhaus (2015) states that there is no difference in maintenance costs or reliability between the double-reheat units of Skærbæk unit 3 and Nordjylland unit 3 with equivalent single-reheat units operating with 560°C superheat steam; the historic performance statistics are similar. During the first years of operation, there were issues with the distributed control system, the thermo-wells and emergency stop valves, which have since been resolved. The engineers of such units have since developed the Master Cycle, a modified double-reheat cycle that could be used to further improve performance of new build double-reheat plants, which is looked at in detail in Chapter 9.

8 Evaluation of all built double-reheat units

From 1956 to 1998, 60 double-reheat units were built globally, 11 in Germany, 32 in the USA, 2 in Denmark, 13 in Japan, and 2 in Italy; amounting to 27.9 GWe. As there are roughly 8700 operational and decommissioned coal-fired units globally, coal-fired double-reheat units account for less than 0.5% of the total fleet.

For coal-fired units, 7 were built in Germany, 28 in the USA, one in Denmark and one in Italy; a total of 37 units. For gas-fired units, 4 were built in Germany, 3 in the USA, one in Denmark, 5 in Japan, and one in Italy; a total of 14 units. For oil-fired double-reheat units, one was built in the USA and 8 in Japan; a total of 9 units. Most of these units were built in Germany, the USA and Japan in the 1960s and 1970s.

Unfortunately, there is only a small amount of published literature on double-reheat plant, and the majority of this is not available online. This is largely because the majority of the units are 40–60 years old and a significant proportion of the units have been decommissioned.

8.1 Technical performance

Figure 14 shows the gradual increase in unit efficiency and unit size with time. For coal-fired double-reheat units, the electrical efficiency increased from 27% to 47% (LHV) and the unit size increased from 100 to 818 MWe. The steam conditions settled on 580°C/580°C/580°C/29 MPa in the 1990s, despite starting at much higher numbers in the 1950s, such as 649°C/565°C/565°C/34.5 MPa.

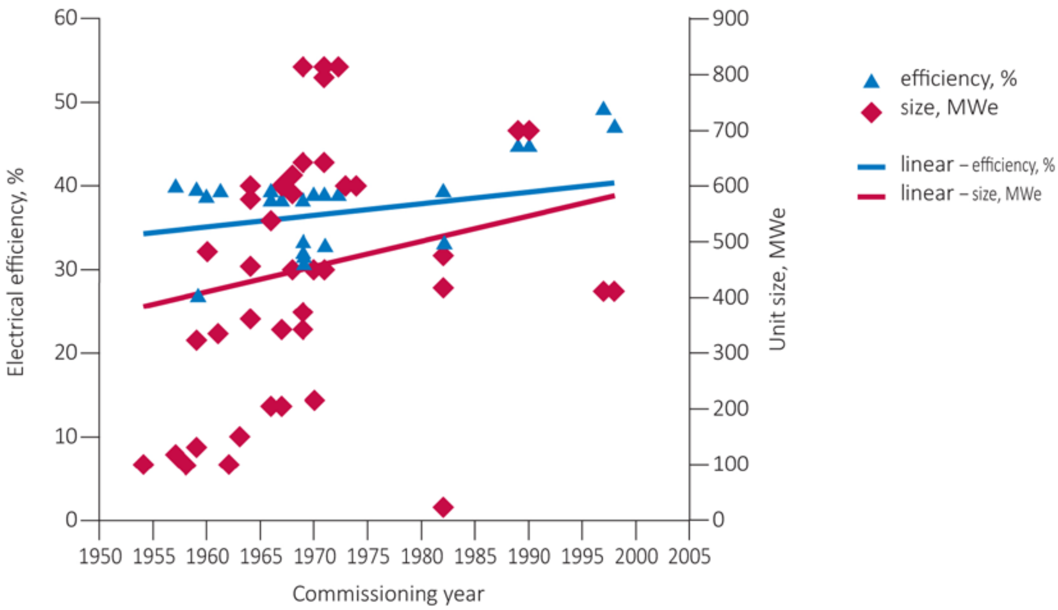

Figure 14 Efficiency and unit size of double-reheat units globally with commissioning year

Numerous engineers have calculated the electrical efficiency increase with double-reheat cycles compared to a single reheat cycle. This figure ranges from 0.8% points to 2% points. The range is due to different reference conditions and technologies used at certain units, and of course method of calculation used:

- 0.8% points, Siemens (MPS, 2010);
- 0.9% points, Dong Energy (Kjaer, 1990);
- 1.4% points (LHV), National Coal Council (2007);
- 1.5% points, Poulsen and Bendixen (2006);
- 1.5% points, Drinhaus (2015): The efficiency difference, at VDE3986 conditions, are 46.7% for a single-reheat (597°C/605°C/28.8 MPa) and 48.3% for a double-reheat (592°C/605°C/605°C/31.1MPa);
- 1.9% points, Chew (2003). Moving from 560/560/25 to 560/560/560/25;
- 2.0% points, Scheffknecht and others (2003).

It is important to note here that such efficiency increases with double-reheat units are valid throughout the load range.

The start-up mode evolved from 100% steam bypass to just a small percentage of bypass combined with sliding pressure operation. Unit reliability and availability were initially poor, due to inexperience with austenitic steels. Since operating at reasonable steam conditions of 530-540°C/538-565°C/530-565°C/24–25 MPa from the mid-1960s onwards and moving to USC steam conditions in the 1990s, double-reheat units have performance records (availability, reliability, cyclic operation) and O&M costs equivalent to those of single-reheat units.

Figure 15 shows net electrical efficiencies (HHV) for some supercritical PCC plant and an approximate value for subcritical plant, firing both black coal and brown coal (lignite). As the efficiency of PCC plant is affected by factors such as location (which affects condenser pressure), coal quality and emission controls, the efficiencies on this figure have been normalised so that comparisons can be made. This figure clearly shows that Nordjylland unit 3 is the most efficient PPC plant, even without the efficiency bonuses of sea water cooling and district heating (IEA, 2007; IEA and others, 2010)

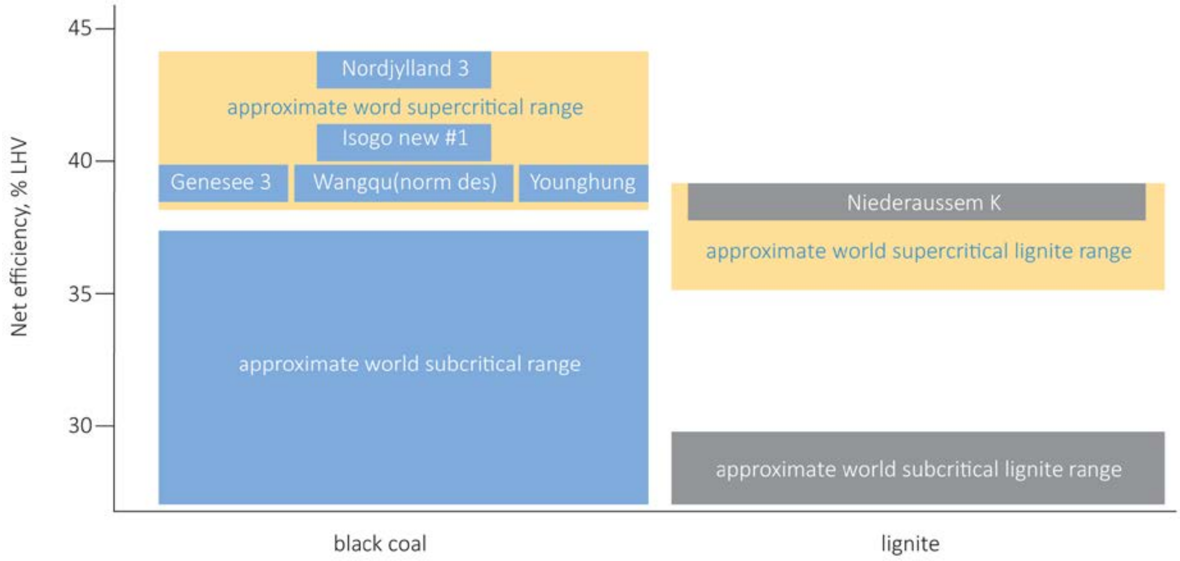

Figure 15 Normalised operating efficiencies of supercritical case study plants compared with elsewhere (IEA, 2007)

8.2 Boiler and turbine manufacturers

In the 1970s, four boilers and one turbine were manufactured by companies in the USA for double-reheat units in Italy and Japan and the international company, GEC-Alstom, manufactured the turbines for the two double-reheat units in Denmark. However, the other 113 boilers and turbines (94%) were commissioned in the country of manufacture.

The dominant boiler manufacturers were: EVT Energie- und Verfahrenstechnik in Germany; Babcock & Wilcox, Foster Wheeler and ABB Combustion Engineering in the USA; Mitsubishi Heavy Industries and Babcock-Hitachi in Japan; and Burmeister & Wain Energy in Denmark. The dominant turbine manufacturers were: Siemens and ABB Power Generation in Germany; General Electric and Westinghouse Electric in the USA; Mitsubishi Heavy Industries and Toshiba in Japan.

8.3 Construction time

Construction times vary considerably depending on site constraints. The construction time for single-reheat PCC plants ranges from 30 to 66 months. Nordjylland unit 3 took 48 months to build. This suggests that longer construction times are not an issue with double-reheat PCC plant (IEA, 2007; IEA and others, 2010).

8.4 Process economics

Additional capital expenditure is required for the second reheat steam loop, but this is eventually paid for with decreased operational expenditures. The coal fuel prices will decide the payback period – generally coal prices increase over time. The trading price of carbon dioxide, or a carbon tax, should be considered in process economics for new double-reheat units, as it is likely that such mechanisms will become established in the next few decades in order to restrict carbon dioxide emissions.

Due to private ownership of the units, and associated commercial sensitivity, specific process economic data for double-reheat units are generally not available. Even so, process economics are date and location specific. For a new unit, the process economics must be calculated with process modelling and simulation software, such as ASPEN Plus or EBSILON Professional, using as much correct information as practical to obtain accurate costs.

A key message to take from the wave and clusters of double-reheat units in Germany, the USA, Japan, Italy and more recently Denmark, is that the process economics of double-reheat units were more favourable than single-reheat units at the time. This will have been due to a combination of low labour costs, which reduces capital costs, and/or high energy prices. Additionally, strong governmental and public forces for environmentally friendly and sustainable energy generation largely favoured double-reheat technology in Denmark.

In 2007 the IEA Clean Coal Centre conducted a major techno-economic analysis of fossil fuel-fired power generation, which included Nordjylland unit 3. These following sub-sections summarise the findings of the report published by the IEA in 2007 (IEA, 2007).

8.4.1 Capital costs

Approximations for the Engineering, Procurement and Construction (EPC) costs were obtained for the selected PPC plant shown in Figure 16. However, these were in different currencies and for different base years. These capital costs were normalised to allow for comparison. These normalisation methods include inflating the cost according to the consumer price index (CPI) rate of inflation and assuming that the interest incurred during construction was 13% of the EPC cost, which gave the overnight capital costs. The owner's costs (cost of land, clearance, initial catalysts and chemicals, start-up costs, spares, fees and working capital) were not included for the plant. However, it was uncertain whether the capital costs given for Younghung and Suratgarh included owner's costs of interest during construction (IDC), so only IDC was added.

This economic analysis contained unquantifiable components – economic, technical and geographical. Economic components, such as currency fluctuations and project financing structure, were not included and would affect these EPC figures. Purchasing power parities (PPP) could be used for a more accurate comparison, but significant data from all parties would be required at the same time for a complete analysis.

The technical components are unit size and plant design. Unit size affects capital costs. Generally, larger units experience economies of scale and therefore lower capital costs. The steam cycle and emission control systems differ with each plant. More detailed information on capital costs is required to quantify costs for such technologies.

Prevailing market conditions at the time play a significant factor. In countries where new units are frequently built, competition is high and work is plentiful, which introduces economies of scale in engineering and in materials procurement, and the costs decrease. The opposite happens to capital costs in countries where new units are rarely built. Furthermore, plant location affects costs for raw materials. To conclude, these figures should be used as an indication for comparison only – none of these figures are absolute.

Figure 16 compares overnight specific capital cost (US$/kWso) versus unit size (MWe). The name Denmark was used instead of Nordjylland unit 3 as the capital costs for Nordjylland unit 3 could not be obtained; values from a front end engineering design (FEED) study for a similar unit in Denmark were obtained. This figure shows that the newer units in Germany and Denmark have higher overnight capital costs. However, these higher figures are likely to reflect increases in the costs of resources and labour over that time period in the OECD, which are not reflected accurately by CPI. This concept is reinforced by the fact that newer units have considerably higher overnight capital costs at >2000 US$/kWso in the OECD.

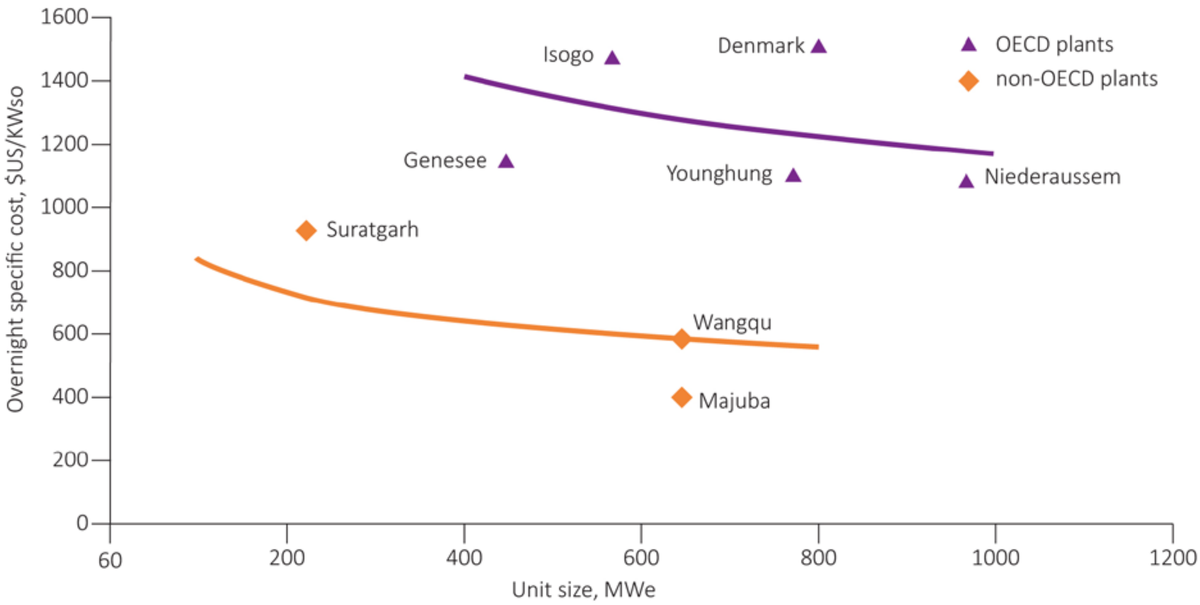

Figure 16 Overnight capital cost with unit size (IEA, 2007)

In 2007, an 800 MWe USC double-reheat unit would cost around 1500 US$/kW, which excludes owner's costs and interest during construction (IDC).

Figure 17 is a plot of adjusted plant costs for a common plant size versus main steam temperature (°C). To draw this graph, the overnight costs of all plant were adjusted to a unit size of 1000 MWe, with an exponential scaling factor of 0.8. Despite the approximate nature of this economic analysis, this graph showed a correlation between the overnight capital cost and superheat steam temperature. This was as expected as higher steam temperatures require higher cost materials.

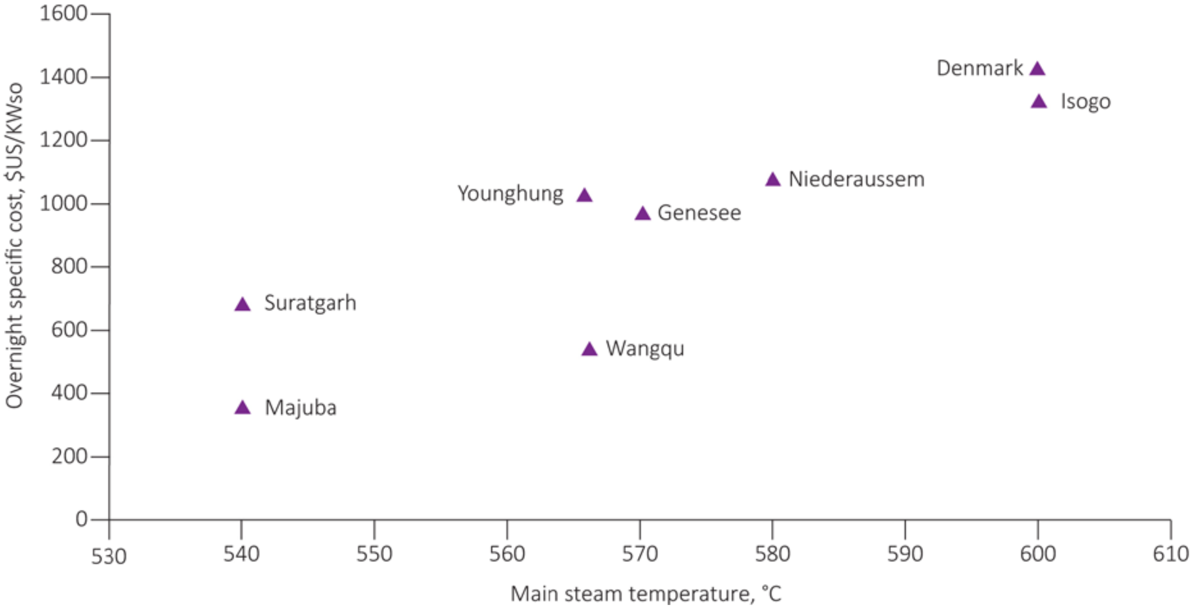

Figure 17 Overnight capital cost versus superheat steam temperature (IEA, 2007)

Figure 18 is a plot of adjusted specific overnight capital cost for a common plant size with normalised net electrical efficiency (%, HHV). As expected, higher efficiencies incur higher capital costs.

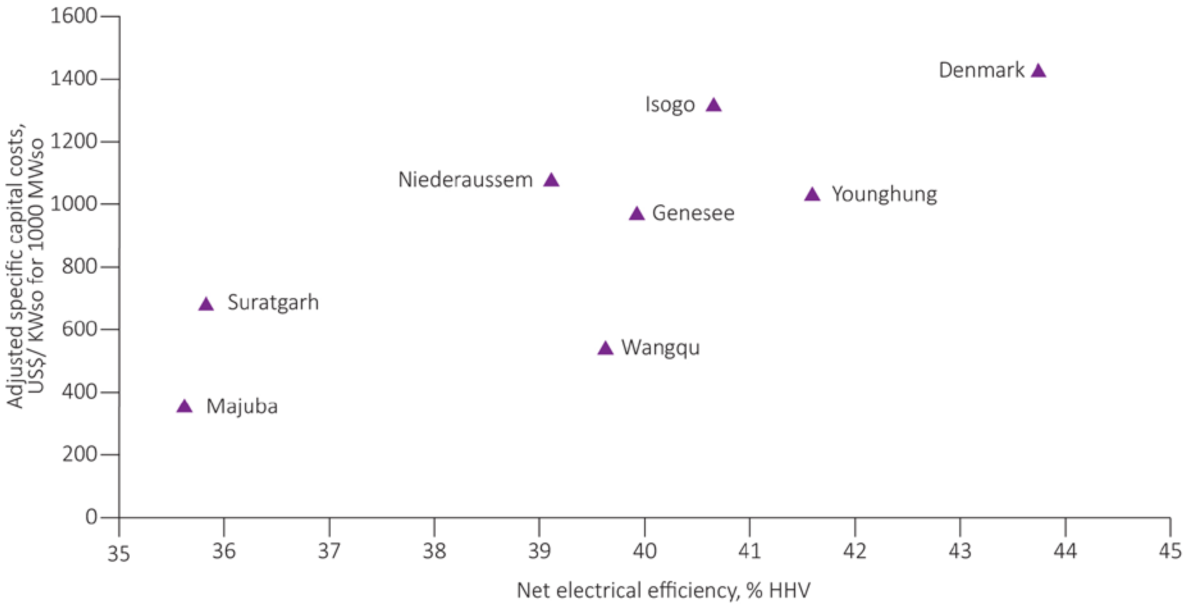

Figure 18 Overnight capital cost with normalised efficiency (IEA, 2007)

8.4.2 Fuel, operation and maintenance costs

Operation and maintenance (O&M) costs, excluding fuel, are the smallest contributor to total plant cost, generally in the range 10–20%. Operating costs include manpower, rates (land taxes), insurance and raw materials (such as limestone, cooling water, boiler feedwater make-up and chemicals). However, in some areas revenue is made from sales of by-products (such as bottom ash, fly ash, gypsum and sulphuric acid).

As a proportion of total plant expenditure, fuel usually represents 30–40% for new coal plants. Present coal costs can be accurately estimated and are similar for the OECD and non-OECD. In 2007, this was 1.5-2.5 US$/GJ (LHV); or 37.5–62.5 US$/t for 25 GJ/t (LHV). However, predicting future coal costs is difficult.

Fuel and O&M costs could only be obtained from two of the eight PCC plant selected, and even those were not complete operating costs and contained some apparently spurious values. These costs had to be based on an amalgamation of IEA Clean Coal Centre knowledge and the data collected.

Levelised generating costs were calculated in the IEA study and are shown on Figure 19, together with the contributions from the main cost elements (overnight capital costs were amortised over 25 years using a real discount rate of 10%). Typically, capital costs contribute around half of total generating costs for coal-fired power plants, and these figures corroberate this. The LCOE is the overall cost of generating electricity which can then be used to compare electricity costs between different units. No carbon tax or carbon trading scheme was included in this study.

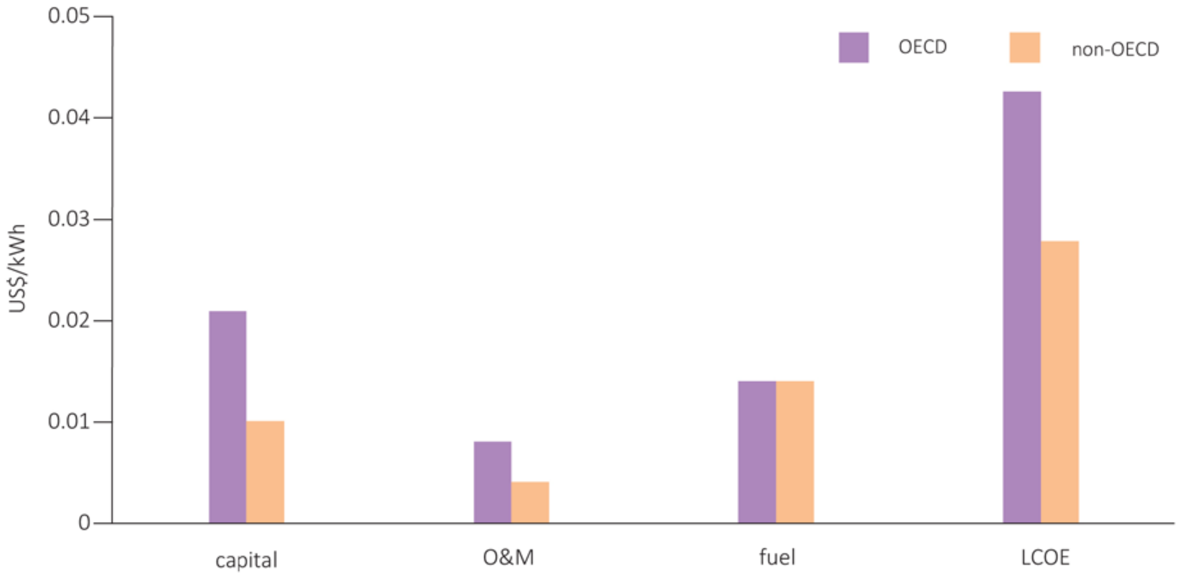

Figure 19 Calculated generating cost contributions for coal-fired power plant in the OECD and Non-OECD countries (IEA, 2007)

8.5 The decline of double-reheat units

Double-reheat cycles fell out of favour in the late 1970s for three reasons. Firstly, nuclear power was introduced for base-load power generation. Secondly, oil prices reduced. Finally, there was a view that the increased capital expenditure and complexity were not economically or technically justified. Gas-fired double-reheat cycles were made redundant with the introduction of combined cycle gas turbine (CCGT) in the late 1990s. Despite this, double-reheat cycles have proved economically favourable in countries with low indigenous energy reserves. The world's most efficient PCC unit, Nordjylland unit 3 in Denmark, employs a double-reheat cycle and was commissioned in 1998.

9 Development prospects for double-reheat units

This Chapter reviews and analyses the recent technical developments and advances in turbines, boiler configuration and steam cycles for double-reheat units.

9.1 Turbine and steam cycle

Double-reheat turbines are made by Alstom, Doosan Heavy Industries, General Electric, Hitachi, Mitsubishi Heavy Industries, Siemens, Shanghai Turbine Works and Toshiba. Developing a design for double-reheat takes decades. Doosan Heavy Industries in Korea manufacture turbines based on a licence from General Electric. Shanghai Turbine Works manufacture turbines based on foreign licences, such as Siemens in Germany. The following sub-sections review the latest developments in turbine and steam cycle technology.

9.1.1 Siemens

Siemens manufacture turbines for use with gas, coal and nuclear power plant which range from 0.3 to 1900 MWe. For large-scale, coal-fired power generation, Siemens manufacture the SST-5000 and SST-6000, which supply 750 MWe and 1200 MWe respectively. Figure 20 shows a 1000 MWe tandem-compound single-train double-reheat turbine, with three LP modules (Quinkertz, 2014).

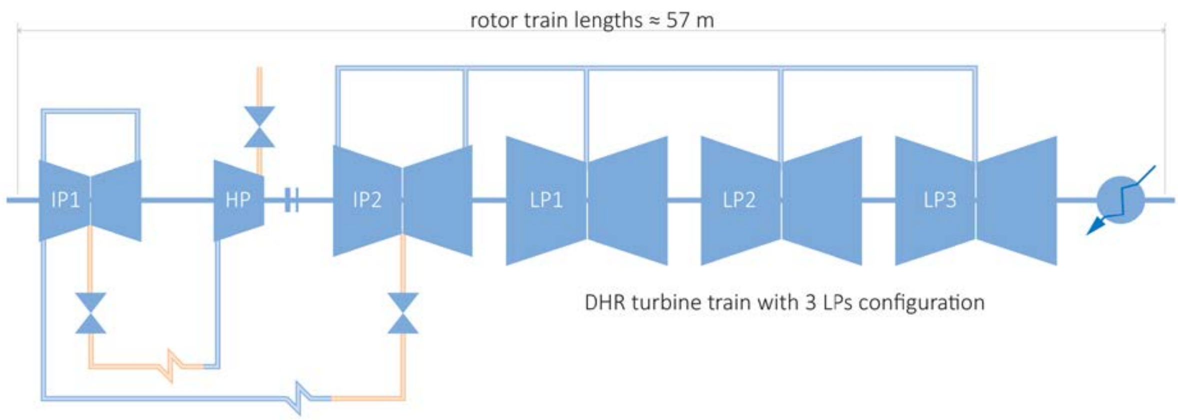

Figure 20 Schematic of Siemens 1000 MWe tandem-compound double-reheat turbine (Quinkertz, 2014)

Siemens are working on an advanced single-train, double-reheat design, shown in Figure 21, which employs increased steam conditions, advanced sealing, an optimised cold end and steam cycle (Quinkertz, 2014).

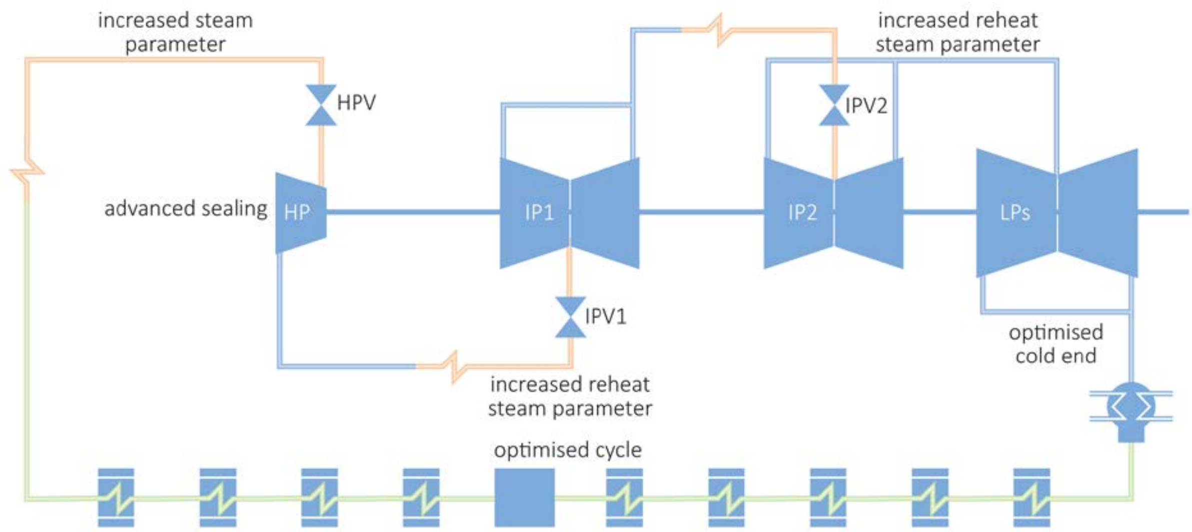

Figure 21 Schematic of Siemens advanced double-reheat turbine (Quinkertz, 2014)

9.1.2 Master Cycle

As superheat steam conditions increase, some of the turbine bleeds for feedwater preheating become too hot (>300°C). This is known as the 'superheat problem', and it is more detrimental to double-reheat cycles than single-reheat cycles. However, the superheat problem would also be significant on single-reheat AUSC units operating superheated steam over 700°.

You will find the superheat problem also on single reheat units, if AUSC temperatures in the range of 700°C are used. In order to exploit the bleed in an optimum way, topping de-superheaters are needed, which are costly.

DONG Energy have devised and patented a modified double-reheat cycle, called the Master Cycle which solves the superheat problem and modifies the steam cycle to increase electrical efficiency and decrease capital costs (Kjaer and Drinhaus, 2010a,b; MPS, 2008).

Steam cycle

The Master Cycle moves the IP turbine bleeds to an additional small turbine, known as the tuning turbine, or T turbine. The T turbine is fed by steam from the first cold reheat steam line. The steam flow through the reheater tubing in the boiler, the associated piping and IP module, is reduced by the amount of bleed steam shifted to the T turbine, which is approximately 15–30%. Essentially, the Master Cycle moves the heat uptake from the two reheaters to the furnace walls and superheaters. This means significant size reductions in reheater tubing and piping, and the IP turbine.

As the bleed temperatures are not as high from the T turbine lower cost steels for the bleed tubing, as well as the stop and check valves, can be used; thus reducing capital costs. Therefore, the Master Cycle significantly reduces the capital costs of double-reheat cycles by reducing the need for high temperature material. The final feedwater can still reach an optimum 330°C with preheating, without compromising the performance of large state-of-the-art single-line rotating air preheaters.

Figure 22 shows a PFD of the Master Cycle. The components in the green box are altered from a conventional double-reheat cycle (Kjaer and Drinhaus, 2010a,b).

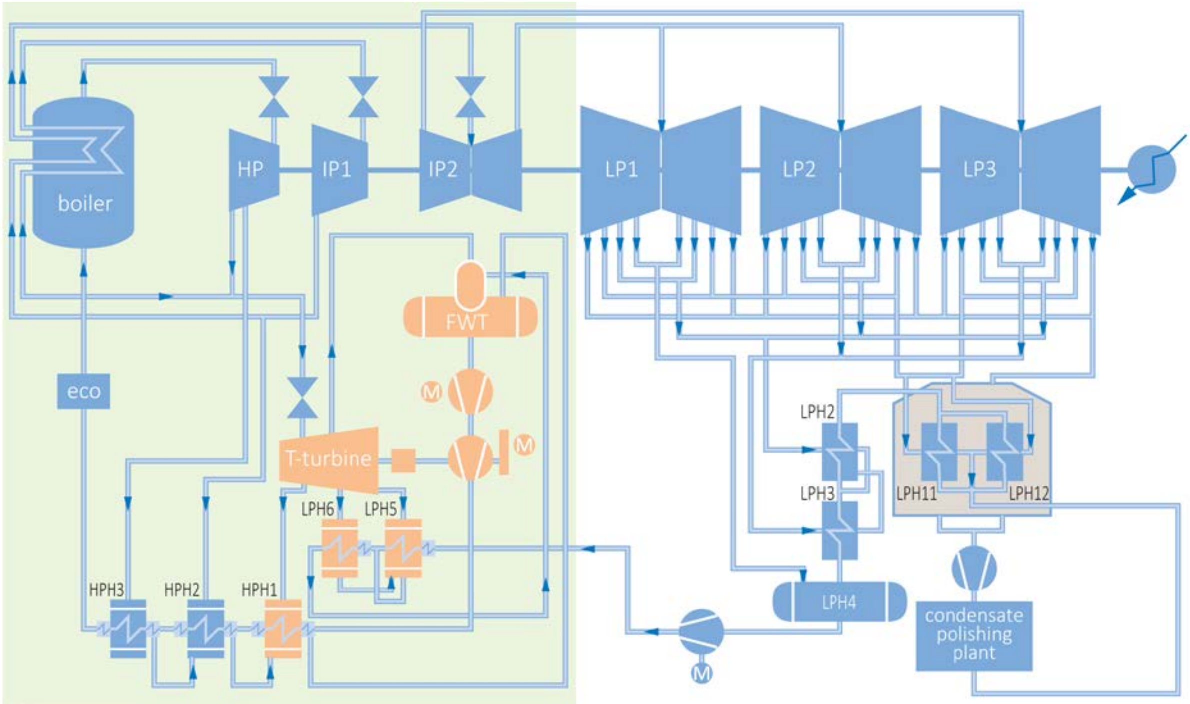

Figure 22 PFD of the Master Cycle (Kjaer and Drinhaus, 2010a,b)

Boiler feedwater pump

In modern supercritical PCC plant, the boiler feedwater pumps (BFP) are driven with condensing turbines or electric motors. The condensing turbines take a steam bleed from the main turbine. Electric motors require an auxiliary load of 20 MWe. Most units have three BFPs driven by condensing turbines, each sized to supply 50% of the maximum feedwater flow rate, and one BFP driven by motors for start-up (MPS, 2010).

The mechanical output from a T turbine could drive a BFP, as the T turbine is similar in size to a condensing turbine used to drive BFPs. A variable speed 'balancing' motor can be used to guarantee the correct speed of the BFP at high loads; at low loads this balancing motor can be used as a generator. For a 900 MWe USC Master Cycle, the balancing motor is sized at 4-5 MWe.

As the steam exiting the T turbine ends in the IP heater, the complicated condenser and cooling water systems with conventional condensing turbine driven BFP, and the associated building structure, are avoided. This configuration is already operational in Avedøre unit 1.

The T turbine could be used with its own generator, but this is unfavourable for a number of thermodynamic and practical reasons (Kjaer and Drinhaus, 2010a,b; MPS, 2008).

Boiler configuration

As the IP bleeds are moved to the tuning turbine, there is 15–30% less steam flow in the reheat piping. This reduces the amount of reheater tubing in the boiler by 6%, thus decreasing capital costs of the boiler. Figure 23 shows a side view of a Master Cycle USC boiler. From bottom to top the order is as follows: furnace screen, which includes the primary superheater (SH1); final superheater (SH3); final primary reheater (RH1.2); final secondary reheater (RH2.2); secondary superheater (SH2); first section of secondary reheater (RH2.1); first section of the primary reheater (RH1.1); final section of the economiser; selective catalytic reduction (SCR); first section of the economiser; and finally the rotating air preheater (Kjaer and Drinhaus, 2010a,b).

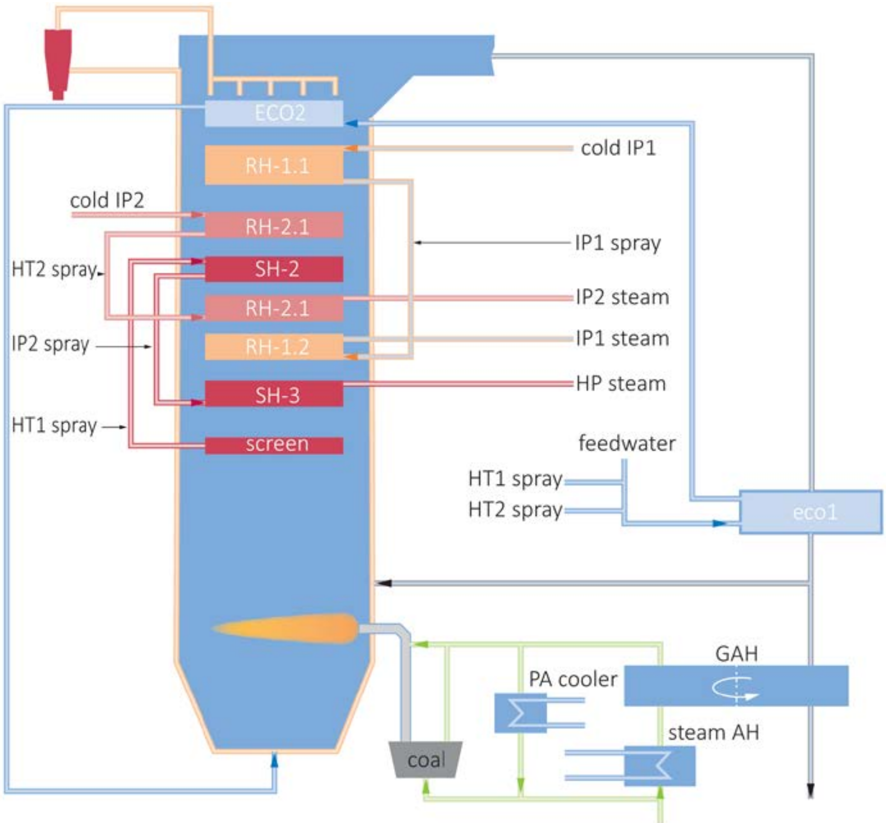

Figure 23 Cross-sectional diagram of a USC Master Cycle boiler (Kjaer and Drinhaus, 2010)

Performance improvement

Relative to a conventional single reheat cycle, the Master Cycle increases the heat rate of the steam cycle by 3–4%, which equates to an increase of net electrical efficiency by 1–2% points (MPS, 2008; IEA, 2007). The paper by Kjaer and Drinhaus (2010a) details the thermodynamic gain from a Master Cycle compared to a single-reheat cycle and a conventional double-reheat cycle, and how the optimum steam temperature and pressures, and final feedwater temperatures are calculated. For a 900 MWe USC unit, they calculated 48.5% net efficiency (LHV) for the Master Cycle unit, 48.45% for a conventional double-reheat cycle and 47.05% for the single-reheat cycle. The Master Cycle has 1.45% points more efficiency than the single-reheat. Although the Master Cycle only has 0.05% points more efficiency than the conventional double-reheat cycle, the superheat problem is avoided and the capital costs are decreased. The Master Cycle does not affect the flexibility of the double-reheat unit.

DONG Energy have calculated that a finely tuned sea-water cooled Master Cycle could reach 49% efficiency. Further process improvements gained by employing best available technologies (BAT) could further increase such efficiency to >50%. The efficiency improvements given by the Master Cycle remain the same for inland located plant with air-cooled condensers (Kjaer and Drinhaus, 2010a,b). Ploumen and others (2011) found that the Master Cycle on a single-reheat unit could increase the electrical efficiency of the unit by 0.4% points.

The Master Cycle is based on well-proven technology and has similar elements to the double-reheat units in the USA, such as Eddystone units 1 and 2 and Philo unit 6 which have excellent operational records (Kjaer and Drinhaus, 2010a,b; MPS, 2008).

Process economics

In 2010, Kjaer and Drinhaus compared the capital cost of a conventional single-reheat cycle to a double-reheat Master Cycle on an 800 MWe unit. The Master Cycle gives an extra 35–40 MW for the same coal input. The Master Cycle requires an additional capital expenditure of around €40–45 million and has a specific investment cost of 1150–1250 €/kW. Compared to the conventional single-reheat cycle, the lower fuel costs and reduced carbon dioxide emissions with the Master Cycle are estimated to save a minimum of €180 million in a typical power plant lifetime (Kjaer and Drinhaus, 2010b; Kjaer and Drinhaus, 2010a).

The IEA (2007) showed that a double-reheat 800 MWe USC unit would cost around 1500 US$/kW compared to a single-reheat unit cost of 1200 US$/kW, which excludes owner's costs and interest during construction (IDC). Assuming an exchange rate of 1 US$ = 0.95 €, the Master Cycle reduces specific investment costs of a double-reheat unit by 12–19%. The specific investment cost of a Master Cycle is also comparable to a single-reheat at 1137 €/kW.

Further modification

The Master Cycle was further improved in 2011, through working with Flowserve (USA) and their experience with Philo unit 6. Improvements include: design of the HP preheater; integration of the final feedwater pump; LP heater bi-condensate pumps for each heater; serial condenser coupling; and boiler cold end optimisation. Drinhaus (2015) says that net electrical efficiencies of over 50% (LHV) can be achieved with an USC Master Cycle.

9.1.3 Shanghai Turbine Works

Shanghai Turbine Works manufacture a 660 MWe and a 1000 MWe double-reheat turbine which operate with ultra-supercritical superheat steam at 600°C and 25–35 MPa, and a reheat at 600–620°C. These turbines can reach a plant efficiency of 48% (LHV), with a net coal consumption of roughly 267 g/kWh and associated carbon dioxide emissions of roughly 730 kg/kWh. In September 2014, forty-three 1000 MWe single-reheat and twenty-nine 660 MWe single-reheat turbines were put into operation (Yang and other, 2014). Additionally, Shanghai Turbine Works have devised a strategy to convert single-reheat units into a cross-compound double-reheat by adding an ultra-high pressure module; this strategy can also raise the steam conditions. Shanghai Turbine Works manufacture turbines based on foreign licences (MPS, 2010).

9.1.4 Echelon Cycle

Shanghai Turbine Works have developed the Echelon Cycle, which is a method of regenerative preheating, which reduces the amount of high-cost materials and capital costs, for single and double-reheat turbines. The Echelon cycle uses an additional smaller turbine called the back pressure extraction turbine (BEST), which takes some steam from the exhaust of the HP or VHP module to drive the boiler feedwater pump, as well as supply steam for regenerative feedwater preheating. The Echelon Cycle reduces the amount of expensive high temperature materials used in regenerative preheating. Figure 24 shows a PFD of a double-reheat turbine with an Echelon Cycle. Shanghai Turbine Works plan to demonstrate their Echelon cycle in 2017 (Yang and others, 2014).

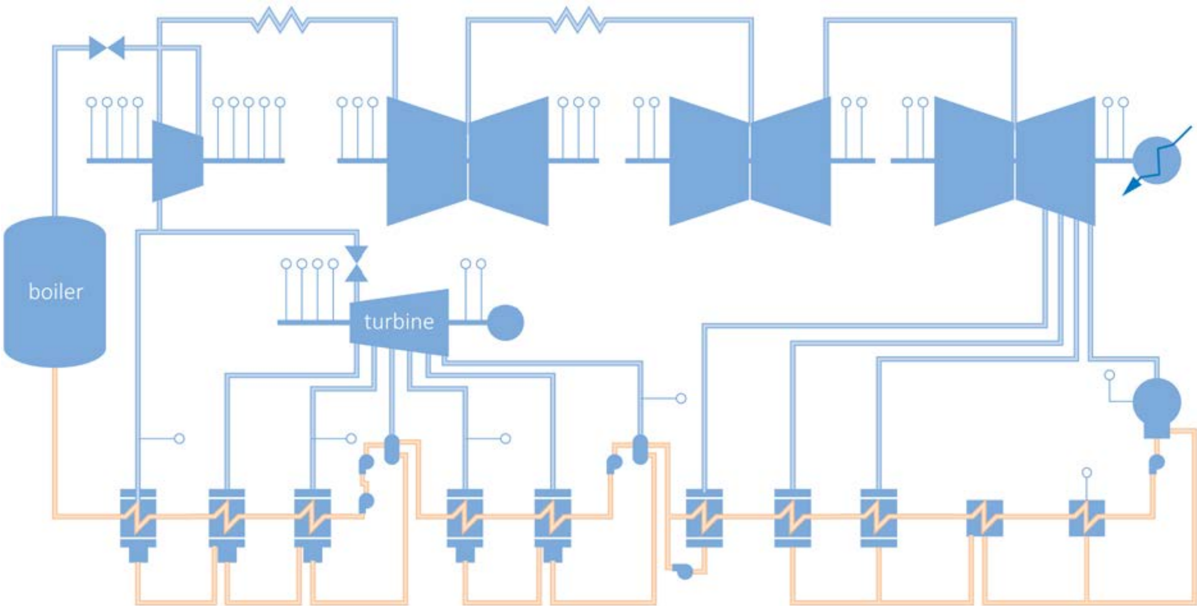

Figure 24 PFD of a double-reheat turbine with an Echelon Cycle by Shanghai Turbine Works (Yang and others, 2014)

9.1.5 North China Electric Power University

Researchers at the National Thermal Power Engineering and Technology Research Center of the North China Electric Power University in Beijing (China) have conducted numerous studies on coal-fired double-reheat cycles.

Outer steam coolers and regenerative turbine (2015)

Xu and others (2015) present two schemes that more efficiently utilise the superheated steam bleeds on a USC double-reheat turbine. A techno-economic analysis for both schemes under full and half-load was conducted. The EBSILON Professional power plant simulation software is used to model the thermodynamic cycles involved. Half-load is assessed because the superheated steam bleed temperature remains constant in sliding pressure units, which means that the superheat problem has more of an effect on unit performance at lower loads.

The results are compared to a reference 1000 MWe double-reheat unit with the following steam conditions 600/610/610/30 and eight stages of steam bleeds, which reaches 46.83% electrical efficiency, as shown in Chapter 2. The reference double-reheat unit has the superheat problem with steam bleeds 2 and 5, which are both first stage IP module bleeds. Bleeds 2 and 5 can reach 562.6°C and 521.7°C, respectively.

The first method is to employ outer steam coolers, as shown on Figure 25. Outer steam coolers use an additional heat exchanger to heat high temperature feedwater before heating low temperature feedwater. This means that the superheated steam bleed is cooled by up to 100°C before heating the low temperature feedwater, which uses the heat more efficiently.

Outer steam coolers are known as feedwater de-superheaters in Europe (or less frequently a topping de-superheater), they are well known and lots of units employ them.

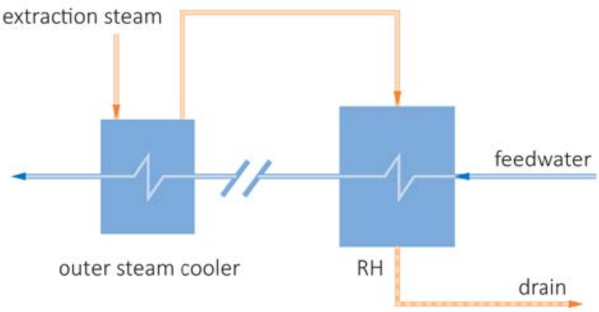

Figure 25 PFD of an outer steam cooler (Xu and others, 2015)

Outer steam coolers would be required on steam bleeds 2 and 5, shown in Figure 26, which is the same configuration as work by Li and others (2014). At full-load, the steam coolers increase electrical efficiency by 0.16% points to 46.99%, or increase the heat transfer rate by 26.2 kJ/kWh, compared to the reference double-reheat unit. At half-load, the increase in electrical efficiency rises to 0.19% points. Assuming a coal price of 4.09 US$/GJ LHV, the total investment for two outer steam coolers is US$2.10 million and the net annual revenue is US$0.29 million. The payback period is therefore 7.2 years for the additional outer steam coolers over the reference double-reheat plant.

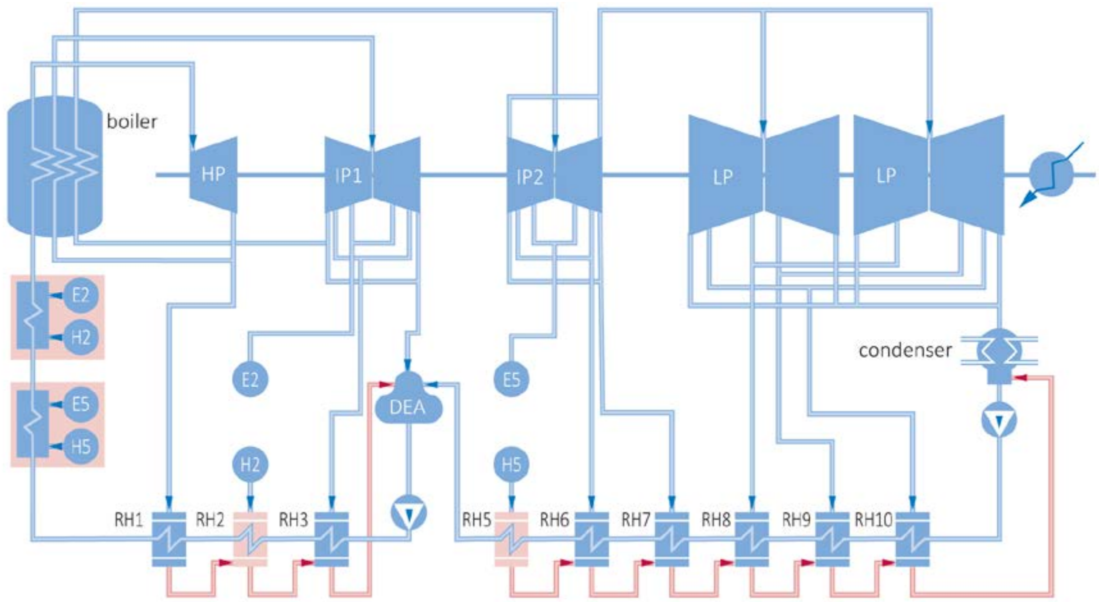

Figure 26 PFD of double-reheat cycle with outer steam coolers (Xu and others, 2015)

The second method is to employ a regenerative turbine, shown in Figure 27. This method is similar to the Master Cycle discussed earlier in this Chapter. At full-load, the regenerative turbine increases electrical efficiency by 0.67% points to 47.5%, and increases the heat transfer rate by 106.80 kJ/kWh, compared to the reference double-reheat unit. At half-load, the increase in electrical efficiency rises to 0.79% points to 47.62%. Assuming a coal price of 4.09 US$/GJ LHV, the total investment for regenerative turbine is US$6 million and the net annual revenue is US$1.59 million. The payback period is therefore 3.8 years for the additional outer steam coolers and regenerative over the reference double-reheat plant.

The regenerative turbine scheme has O&M costs and capital costs that are approximately three times those of the outer steam coolers. However, the higher efficiency increase offsets these costs and the regenerative turbine scheme has almost half the payback period.

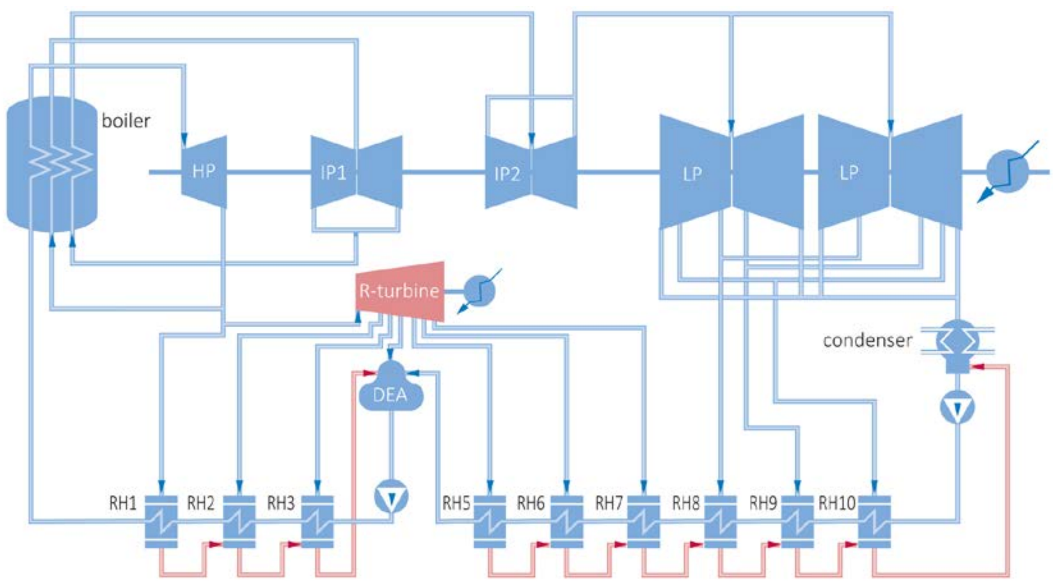

Figure 27 PFD of double-reheat cycle with a regenerative turbine (Xu and others, 2015)

Outer steam coolers (2014)

Li and others (2014) present a similar investigation. A single-reheat unit, with steam conditions of 600°C/600°C/26.25 MPa with 44.78% electrical efficiency is used as a base case.

Case 1 is a double-reheat unit with eight stages of steam extraction for increased feedwater preheating. This would have 46.5% electrical efficiency. Case 2 is a double-reheat unit with ten stages of steam extraction. This would have 46.83% electrical efficiency. Case 3 is a double-reheat unit with ten stages of steam extraction, coupled with two outer steam coolers. Case 3 increases the electrical efficiency of the base case by 2.21% points to 46.99%. The total plant investment is increased by US$45.6 million to US$745.6 million. The annual fuel costs decrease by US$7.74 million to US$157.08 million. The O&M costs increase by US$0.82 million to US$29.82 million. Finally, the LCOE decreases by 0.05 US$/MWh to 55.89 US$/MWh (Li and others, 2014).

9.2 Boiler-turbine configuration

Boilers are made by Foster Wheeler, Babcock & Wilcox, Alstom, Siemens, Shanghai Boiler Works, Harbin Boilers, Rafako and others. Single-reheat PCC plant have 150 metres of pipework between the boiler and the steam turbine, manufactured from high cost materials. Double-reheat plant can have 450 metres of such pipework. The pipework cost accounts for about 3% of the capital costs with conventional single - reheat units (Jeffs, 2000). Therefore, alternative boiler-turbine configurations could reduce the length of the pipework and thus dramatically reduce capital costs.

9.2.1 Compact design boiler

Siemens developed the compact design boiler to shorten steam pipework. This Benson-type boiler uses horizontal firing and raises the turbine plinth, to reduce the amount of expensive high temperature pipework by up to 80%. For a 550 MW unit, the compact design boiler is 31 metres tall, a two-pass boiler is 63 metres tall and a tower boiler is 91 metres tall (Jeffs, 2000). This concept has not yet been demonstrated for a coal-fired boiler. However, a subcritical compact design boiler was installed as a heat recovery steam generator (HRSG) at the Cottam Development Centre test facility in the UK (MPS, 2010). Another arrangement is to have the boiler and turbine inline (MPS, 2008).

9.2.2 Partially underground tower type boiler

Xu and others (2014) at the National Thermal Power Engineering and Technology Research Center of the North China Electric Power University in Beijing (China) propose a novel partially underground tower type boiler design to decrease capital costs of double-reheat units.

This configuration, shown in Figure 28, reduces boiler height by 70 m and steam piping length by 160 m. Compared to a typical 1000 MWe double-reheat design, the submerged boiler increases electrical efficiency by 0.1% point (or increases the heat transfer rate by 18.3 kJ/kWh). The high efficiency and lower investment cost lower the cost of electricity (COE) by 0.60 US$/MWh. Further investigations found that the economics of the partially underground boiler become more favourable with increasing coal prices and high capital costs, especially for potential AUSC double-reheat units which employ high cost nickel alloys.

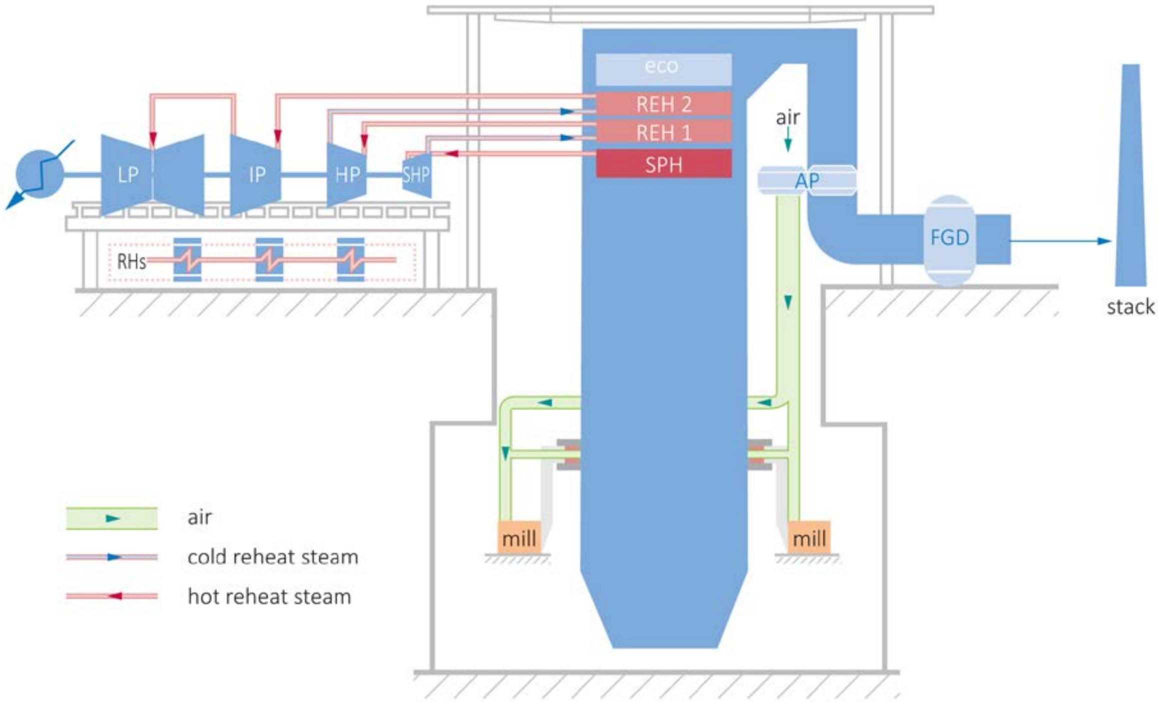

Figure 28 Cross-section of partially underground tower type boiler (Xu and others, 2014)

9.2.3 Cross compound at high/low position arrangement

The plant engineers at Waigaoqiao No 3 PCC plant have designed a turbine configuration which decreases the length of the pipework. This re-design is known as the cross compound at high/low position arrangement (CCHLPA). In this arrangement the turbine is split into two trains. The first train, which consists of the VHP, HP and one IP modules, is mounted at the same level as the outlets of the boiler steam headers, which is around 80–85 metres above ground level. The second train, which consists of the two IP modules and the LP modules, remains roughly 17 m above ground level in the conventional turbine house. Additionally, shorter pipework reduces the pressure drop and temperature loss of steam from the boiler, which slightly increases efficiency. Figure 29 shows a basic schematic of the cross-compound at high/low position arrangement (CCHPLA) technology (Feng, 2014a; Mao, 2012).

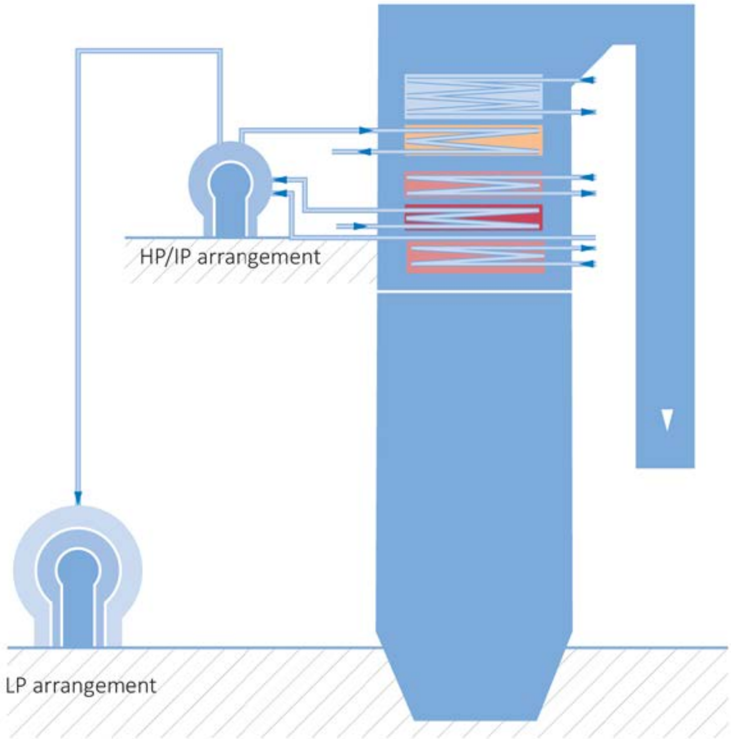

Figure 29 Cross-compound at high/low position arrangement (CCHPLA) technology (Mao, 2012)

10 Double-reheat units proposed and under construction

This Chapter reviews, analyses and evaluated the double-reheat units that are currently in planning and under construction.

10.1 Europe

DONG Energy conducted a preliminary FEED study for a third double-reheat unit in Denmark, in a series of 'Convoy' units, following positive experience with Skærbæk unit 3 and Nordjylland unit 3.

The study involved Alstom, Siemens, Toshiba, Hitachi Power Europe and MAN Turbo. The following steam cycle configurations were assessed, single-reheat, conventional double-reheat and the Master Cycle. The Master Cycle employed a 800 MWe Siemens turbine with the following temperature 590°C/604°C/604°C (Quinkertz, 2014). In 2007, Siemens estimated that an 800 MWe double-reheat USC unit would cost around 1500 US$/kW, which excludes owner's costs and interest during construction (IDC) (IEA, 2007).

However, in 2010 DONG Energy announced that, in order to significantly reduce its carbon footprint, they would not invest in new coal-fired power plants (Drinhaus, 2015).

10.2 China

The following sub-sections analyse the double-reheat units under construction in China and the last sub-section evaluates these units.

10.2.1 Guodian Taizhou 1 and 2

Guodian Taizhou units 1 and 2 are two hard coal-fired double-reheat units under construction and planned to be commissioned in August 2015 (Fan, 2015). Guodian Taizhou PCC plant is made up of two 1000 MWe, double-reheat, USC units, operating at 600°C/610°C/610°C/31 MPa, calculated to reach up to 47.94% efficiency (LHV). Coal consumption is predicted to be 256.2 g/kWh, which is 14 g/kWh lower than an equivalent single-reheat unit, saving 151.8 thousand tonnes of coal annually. The payback period of the incremental capital cost of the double-reheat cycle, compared to single-reheat cycle, is just 6.25 years, which is economically justified considering a plant life of 25 years+. Guodian Taizhou will be the largest double-reheat plant and most efficient coal-fired power plant in the world (China Guodian Corporation, 2015; Yang and other, 2014; Sun and others, 2012; Shanghai Electric, 2012).

Turbine

Guodian Taizhou unit 1 will employ Shanghai turbine Works first double-reheat 1000 MWe turbine. This turbines operates at 600°C/620°C/620°C/29 MPa, but can handle up to 35 MPa superheat pressure. The turbine is made up of a single-flow VHP module, double-flow HP module, double-flow extra-large IP modules, and two double-flow LP modules with 1146 mm last row blades. Extra-large IP modules are required due to the increased volume of steam flow with the superheated steam at 35 MPa. It has a single shaft with five casings, four exhausts and spans 36.7 metres. There are ten stages of re-generative feedwater heating and it has tandem-compound configuration. The turbine uses 9–12% chromium martensitic steels, such as CB2 for cast components and FB2 for forged components (rotor, valve and module casings). Start-up methods have been devised for ultra-high, high and medium pressure starts (Yang and other, 2014). Figure 30 shows a PFD of the 1000 MWe double-reheat turbine (Yang and other, 2014).

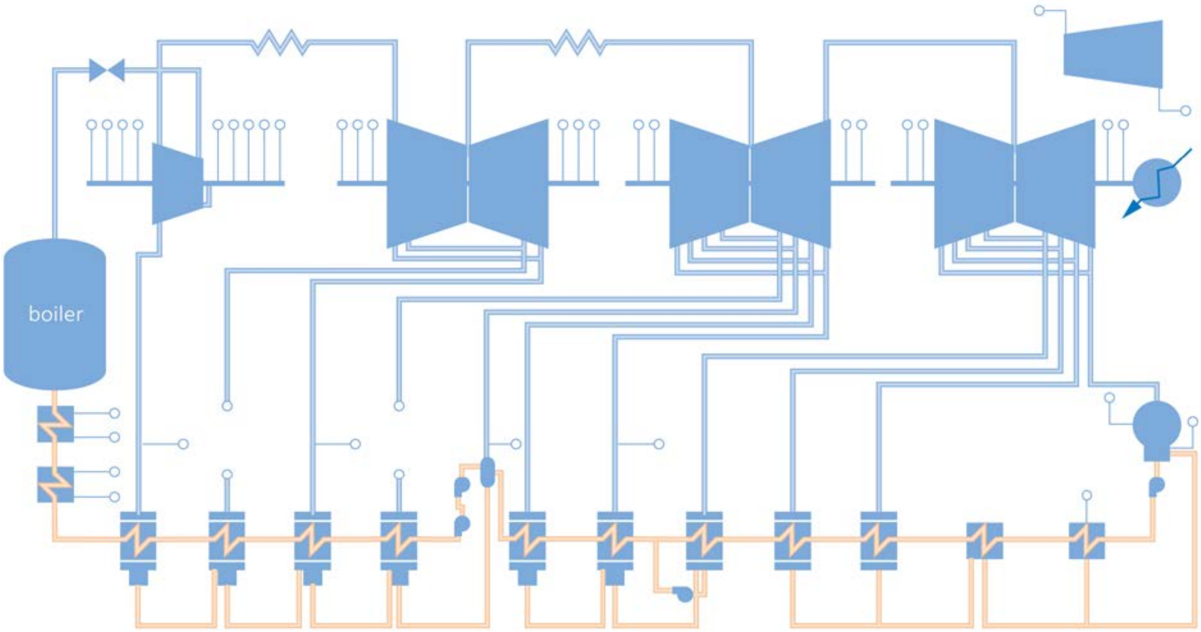

Figure 30 PFD of a 1000 MWe double-reheat cycle by Shanghai Turbine Works (Yang and others, 2014)

10.2.2 Waigaoqiao number 3 unit 9

The Shenneng Group Co Ltd, owners of Waigaoqiao No 3 power plant, have made a number of process improvement and plant innovations which will be highlighted in this sub-section.

Waigaoqiao No 3 power plant consists of two 1000 MW USC units, , known as units 7 and 8, with steam parameters 605°C/603°C/28 MPa, constructed by Shanghai Boiler Works, and two 1000 MW Siemens designed turbines, manufactured by Shanghai Turbine Works. These units were designed, constructed and commissioned in just over three years, from 2005 to March-June 2008, at a cost of 8.5 billion Yuan RMB (1.2 billion US$). During the project construction, the engineers carried out a large number of optimisations and technological innovations in all aspects of project design, equipment selection, construction, commissioning, start-up and operation. Units 7 and 8 at Waigaoqiao No 3 power plant now operate with higher efficiency and lower emissions than originally designed. The average net electrical efficiency, from January to August 2014, was 44.35% (LHV) and the average load is 78%, which equates to 276.82 g/kWh. For the same time period the average NOx, SO_2 and particulate emissions were 16.61, 32.96 and 9.92 mg/m^3 respectively – all well within the regulated limits of 100, 50 and 20. In 2013 the plant, at full-load, reached 46.7% net efficiency, with only 2% auxiliary load (Feng, 2014b).

The next major efficiency improvement at Waigaoqiao will be a new build, known as unit 9. This unit will use a double-reheat cycle with the CCHLPA unit configuration as explained in Chapter 3 and incorporate the efficiency improvements made at unit 7 and 8. It has been independently verified by Siemens, Alstom and Chinese local manufacturers to reach around 48.9% net electrical efficiency (LHV), which equates to roughly 251 g/kWh (Feng, 2014a; Quinkertz, 2014; Mao, 2012). The owners of Shanghai Waigaoqiao No 3 have permission from the Chinese Government and the Chinese National Energy Administration to build unit 9. Construction will start in 2015, operation is expected in 2017 and the payback period is expected to be less than five years (Feng, 2014b).

Calculations have shown that if Waigaoqiao No 3 unit 9 was built on the Danish coast with access to cooling water at an average of 10°C then the plant could reach 51% net electrical efficiency (LHV). Additionally, if advanced ultra-supercritical (AUSC) technology were used with steam parameters of 700°C/720°C/720°C/35 MPa then 52% net electrical efficiency (LHV), or 236 g/kWh could be reached in Shanghai, or an incredible 54% net electrical efficiency (LHV) if located in Denmark (Feng, 2014b).

The turbine, designed by Siemens, is a cross-compound type with double-reheat operating at the following USC steam parameters 600°C/620°C/610°C/30 MPa. The primary-reheat pressure is 9.17 MPa and the secondary-reheat pressure is 2.25 MPa. The rated steam flow rate is 3229 t/h and the maximum steam flow is 3426 t/h. The average cooling water temperature is 19°C. This turbine generates 1350 MWe and a schematic and 3D model, showing the first and second trains, are shown in Figures 31 and 32 (Quinkertz, 2014).

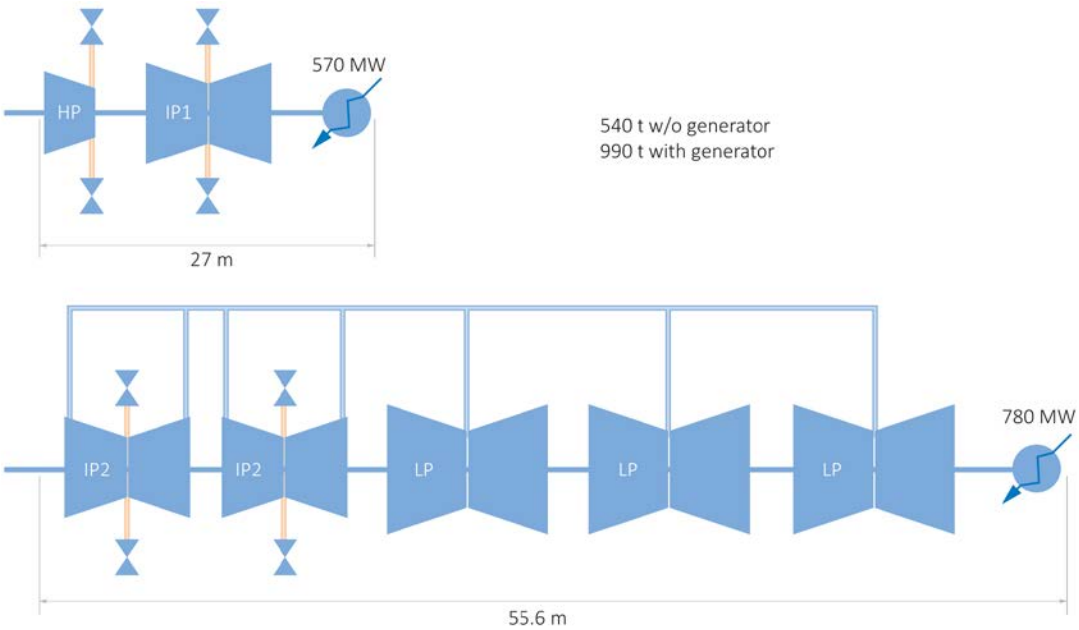

Figure 31 PFD of the Siemens 1350 MWe turbine (Quinkertz, 2014)

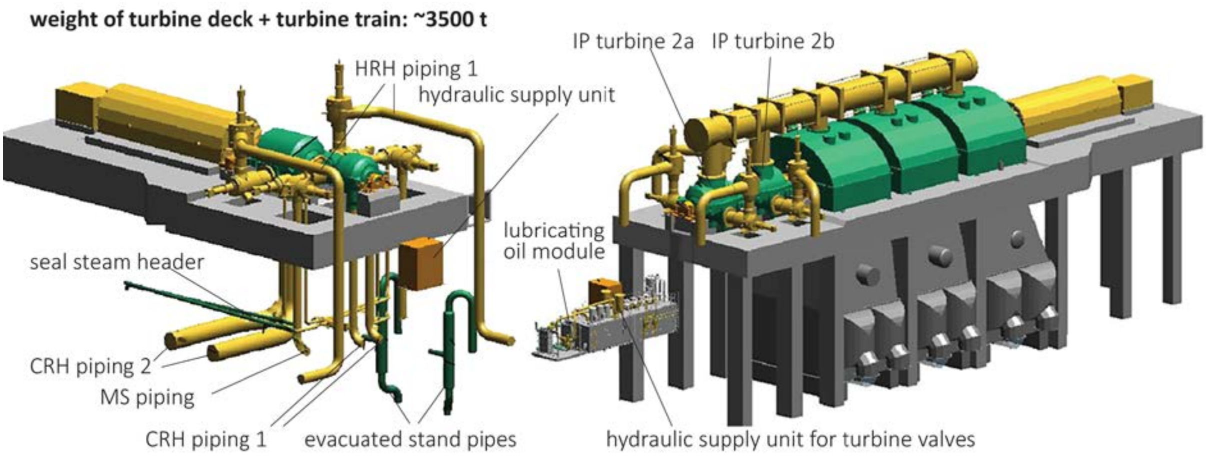

Figure 32 3D model of the Siemens 1350 MWe turbine (Quinkertz, 2014)

10.2.3 Laiwu 6 and 7

Laiwu units 6 and 7 are two hard coal-fired double-reheat units under construction and should be commissioned in mid-2015 (Yamauchi, 2015). They are owned by Huaneng Shandong Power. Harbin Boiler Company is building the boiler and Shanghai Turbine Works are building the turbine. They are both 1000 MWe USC units with the following steam conditions 600°C/620°C/620°C/31 MPa (Platts, 2014).

10.2.4 Huaneng Anyuan 3 and 4

Huaneng Anyuan units 3 and 4 are two hard coal-fired double-reheat units under construction and should be commissioned in mid-2015. They are owned by Huaneng Power International. Dongfang are building the boiler and turbine. They are both 660 MWe USC units with the following steam conditions 600°C/620°C/620°C/31 MPa (Platts, 2014).

10.2.5 Yuedian Huilai 1 and 2

Yuedian Huilai units 1 and 2 are two hard coal-fired double-reheat units under construction and should be commissioned in mid-2015. Shanghai Turbine Works are building the turbine. They are both 1000 MWe USC units with the following steam conditions 600°C/620°C/620°C/31 MPa (Fan, 2014; Yang and others, 2014).

10.2.6 Guohua Beihai 1 and 2

Guohua Beihai units 1 and 2 are two hard coal-fired double-reheat units under construction (as of 2014) and will be commissioned in 2015. Shanghai Turbine Works are building the turbine. They are both 1000 MWe USC units with the following steam conditions 600°C/620°C/620°C/31 MPa (Fan, 2014; Yang and others, 2014).

10.2.7 Guodian Bengbu 1 and 2

Guodian Bengbu units 1 and 2 are two hard coal-fired double-reheat units under construction and should be commissioned in mid-2015. Shanghai Turbine Works are building the turbine. They are both 660 MWe

USC units with the following steam conditions 600°C/620°C/620°C/31 MPa (Fan, 2014; Yang and others, 2014).

10.2.8 Analysis

In 2012, PCC plant in China accounted for 80% of installed power generation capacity and coal-fired power plant accounted for approximately half of China's total carbon dioxide (CO_2) emissions. From 2012 to 2020, 400 GWe of new coal-fired power generation will be required, which equates to roughly 50% additional capacity.

However, China currently has serious problems with air pollution; an example of this is that visibility in Beijing can be reduced to 2 km. Therefore, the Chinese Government has enforced lower emission standards for coal-fired power plant, of 5 mg/Nm^3 PM, 35 mg/Nm^3 SO_2 and 50 mg/Nm^3 NOx and a limit for mercury. Additionally, new build coal-fired power plant have been banned on the east coast of China, except for Waigaoqiao No 3 unit 9. Increasing PCC plant efficiency is therefore an effective way to comply with the increasingly stringent emission limits and to prolong valuable coal resources. The efficiency of China's coal fleet has significantly increased from extensive R&D and deployment of upgrades and efficiency improvements, the demolition of old small subcritical units and the construction of new large USC units. The average coal consumption is now 321 g/kWh, down from 380 g/kWh ten years ago, which is the third lowest in the world after Japan and Germany, both at 290 g/kWh. Additionally, close to a third of the coal-fired fleet is fitted with CHP. Further improvements in efficiency will be met with larger units, double-reheat and higher steam parameters.

With relatively high coal prices coupled with low labour costs, double-reheat USC units are seen as an economically favourable, technically feasible and more environmentally friendly means of coal-fired power generation. Double-reheat technology was identified as a key R&D project for China's 'Twelfth Five-year Plan (2011-2015)' (Xu and other, 2015; Li and others, 2014).

Thirteen units are currently under construction in China, amounting to 11 GWe, and twelve units should be commissioned this year. Table 5 lists the hard coal-fired double-reheat units under construction in China, with details of year commissioned, primary fuel, size (MWe), steam conditions (°C/°C/°C/MPa) and electrical efficiency (%), in chronological order of year commissioned. By late 2015, the two new units at Guodian Taizhou should be the largest and most efficient coal-fired double-reheat in the world, at 1000 MWe each reaching 47.94% electrical efficiency (LHV). Further advances in plant configuration and steam cycle are planned to be demonstrated in 2017.

Table 5 List of coal-fired double-reheat units under construction in China

Unit	Planned commissioning Year	Primary Fuel	Size (MWe)	Steam Conditions (°C/°C/°C/MPa)	Electrical efficiency (%)
Laiwu 6	2015	Hard coal	1000	600/620/620/31	
Laiwu 7	2015	Hard coal	1000	600/620/620/31	
Huaneng Anyuan 3	2015	Hard coal	660	600/620/620/31	
Huaneng Anyuan 4	2015	Hard coal	660	600/620/620/31	
Yuedian Huilai 1	2015	Hard coal	1000	600/620/620/31	
Yuedian Huilai 2	2015	Hard coal	1000	600/620/620/31	
Guohua Beihai 1	2015	Hard coal	660	600/620/620/31	
Guohua Beihai 2	2015	Hard coal	660	600/620/620/31	
Guodian Bengbu 1	2015	Hard coal	660	600/620/620/31	
Guodian Bengbu 2	2015	Hard coal	660	600/620/620/31	
Guodian Taizhou 1	2015	Hard coal	1000	600/610/610/31	47.94
Guodian Taizhou 2	2015	Hard coal	1000	600/610/610/31	47.94
Waigaoqiao 9	2017	Hard coal	1000	600/620/610/30	48.92

11 Advanced ultra-supercritical double-reheat units

This Chapter explains the concept of advanced ultra-supercritical (AUSC) technology, reviews the research and development (R&D) programmes globally with the prospects for combination with double-reheat cycles.

11.1 AUSC technology

The steel barrier presently lies at 620°C. Current research aims to use nickel alloys to reach 700°C superheated steam, known as AUSC or 700°C technology, with a corresponding net electrical efficiency greater than 50% (LHV). Double-reheat cycles combined with AUSC steam conditions could provide lucrative gains in electrical efficiency. When operating with 700°C superheat steam, double-reheat cycles would increase the efficiency over single-reheat cycles by +0.7% points (Weitzel, 2012) and +2% points (HHV) (Viswanathan, 2010).

The pressures in AUSC turbines are higher those in USC turbines; the secondary hot reheat pipe would have a pressure of around 2.1 MPa. Therefore, controlling the temperature/pressure differential between the HP, IP1 and IP2 modules is complex and restricts the turbine operating range. The benefit of increased efficiency must be weighed against higher capital costs and restricted operating range. It is likely that the first AUSC units will employ single-reheat and once significant operational experience has been gained then double-reheat could be employed if justified (Weitzel, 2012).

11.2 AUSC research and development programmes

The EU, USA, Japan, India and China all have material R&D programmes for 700°C technology. Nicol (2013) has reviewed the developments and status of these major material research programmes. The material research programmes consist of the following three main stages, which can overlap each other by a few years depending on technical readiness and funding availability:

- Stage 1: Small-scale laboratory tests (8–13 years);
- Stage 2: Large-scale components test facility (CTF):
  - Part A: Design and build (4–5 years);
  - Part B: Operate and evaluate (3–5 years);
- Stage 3: Full-scale demonstration plant (FSDP) (500–1000 MWe):
  - Part A: Design and build (4–6 years);
  - Part B: Operate and evaluate (6 years).

Figure 33 shows a Gantt chart of the material research programmes. Assuming successful operation of a full-scale demonstration plant, commercial 700°C AUSC PCC power plant could be operation in 2031, given favourable economics. Progress has been slower than expected, which has led to increased demand for 650°C steels.

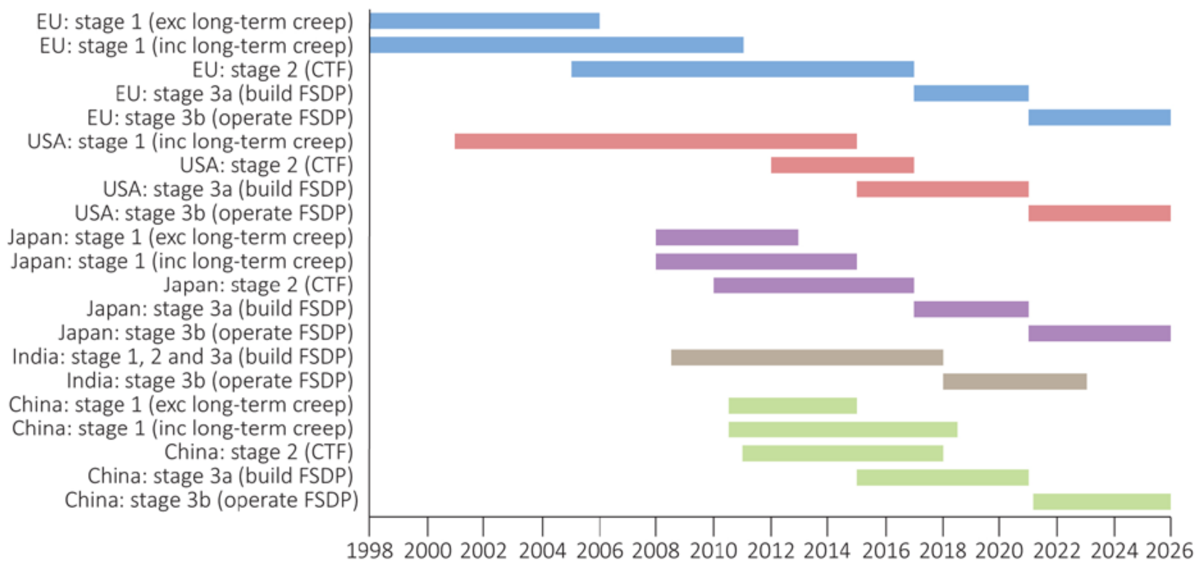

Figure 33 Gantt chart comparing the AUSC material research programme timelines (Nicol, 2013)

Compared to ferritic and martensitic steels, nickel alloys have a high coefficient of thermal expansion and low thermal conductivity. This means that nickel alloys are slow to react to temperature change, and expand and contract at rates which could result in cracking. Therefore, AUSC technology would be best suited to base-load operation.

11.3 Proposals for AUSC double-reheat systems

The AUSC R&D programmes in Europe, the USA, Japan and China include plans for a full-scale demonstration plant (FSDP). A smaller unit size of approximately 500–600 MWe has been chosen in all programmes to minimise financial risk to investors. This section reviews how the AUSC R&D programmes are incorporating double-reheat technology.

11.3.1 Europe

The European AUSC R&D programme conducted a detailed FEED study to determine the technical and economic feasibility of a 500 MWe demonstration AUSC PCC unit fired with bituminous coal. The FEED study, called the North Rhine-Westphalia Power Plant at 700°C (NRWPP700), began in October 2006 and ended in 2008. The study was completed by a consortium of twenty power plant operators and component suppliers involved in the European AUSC R&D programme; the study was co-ordinated by the VGB. Over 70% of the funding came from the consortium and the remainder from regional funds from Brussels via the government of North Rhine-Westphalia.

On the boiler side, three tower boiler concepts from Alstom, Hitachi Power Europe, Burmeister and Wain Energy were assessed. Alstom designed a high pressure (36.4 MPa) single-reheat boiler and Hitachi Power Europe designed an intermediate pressure (26.4 MPa) single-reheat boiler.

The single-pass tower boiler from Burmeister and Wain Energy was a design for the Master Cycle concept, with the following steam conditions 702–705°C/720°C/720°C/36.4 MPa (at boiler outlet). The primary reheat pressure is 7.5–11.2 MPa and the secondary reheat pressure is 2.5–2.7 MPa. The advantages of this design are lower use of expensive nickel alloys, through smaller primary and secondary reheaters with the Master cycle, and a relatively compact boiler with the tower arrangement. Additionally, tower boilers are easier to operate than two-pass boilers. Preliminary thermodynamic calculations estimated the boiler efficiency at around 95%, which led to a net unit efficiency of 50.18% (LHV).

Figure 34 shows the piping layout of the Master Cycle boiler by Burmeister and Wain Energy. The membrane walls are planned as evaporators (EVAP). The reheater is split into three parts. SH1 and SH2 are arranged in counter flow to the flue gas, SH3 in co-current flow. The reheater (RH) is divided into a first and a second reheater group. RH1 and RH2 are combined with each other in their arrangement. The reheat temperatures are kept to 720°C, up to 100% load, with the use of excess air and injection coolers. Economiser 1 (ECO1) is arranged in counter flow to the flue gas. The second economiser (ECO2) is planned with an up-flow parallel to the flue gas flow. This arrangement minimises the risk of evaporation in the second economiser. The economiser was split that way so that in part load operation the temperature can be controlled for the downstream nitrogen oxide catalyst, or selective catalytic reduction (SCR). Thus, a relatively high temperature before the SCR must be accepted in full load.

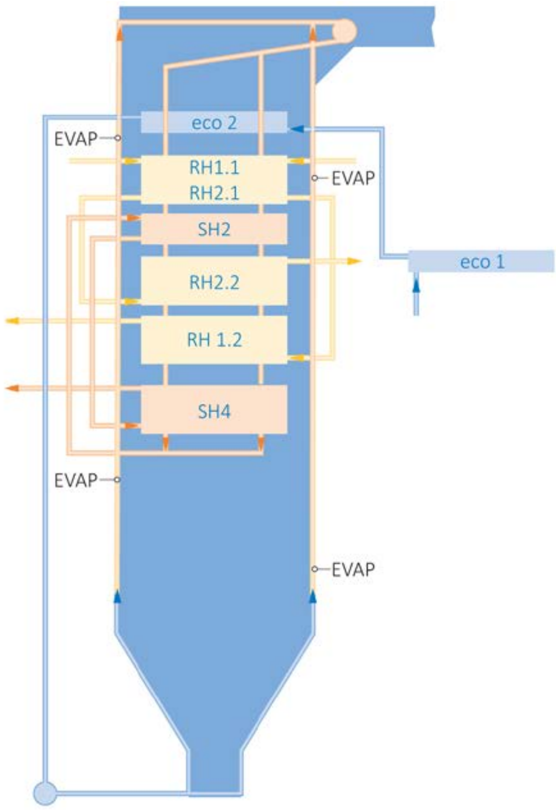

Figure 34 Piping layout of Master Cycle boiler by Burmeister and Wain Energy (VGB, 2012)

Although the Master Cycle concept boiler and the high pressure single-reheat boiler by Hitachi Power Europe had similar technical and economic viability, the Master Cycle boiler was rejected because the main turbine, and tuning turbine, could not be built with the standardised modular unit assembly system of the turbine manufacturers. The components would have to be newly developed, which increases the capital expenditure.

It was decided to opt for the high pressure single-reheat boiler with steam parameters of 705°C/720°C/36.5 MPa reaching 49.8% net electrical efficiency (LHV). In 2012, the capital cost for this demonstration unit was €1.7 billion, or >3000 €/kW. In comparison, a modern supercritical PCC plant built in the developed world in 2012 would cost <1200 €/kW (VGB, 2012). It was estimated that a 1100 MWe commercial version of a high pressure single-reheat boiler could reach 50.2% net electrical efficiency (LHV) on coastal sites. The Master Cycle could improve such efficiency by 1–2% points; therefore a Master Cycle AUSC unit could reach 52.2% net electrical efficiency (LHV) on coastal sites (MPS, 2008; IEA, 2007). In 2010, the FSDP was postponed due to technical problems (such as cracking of thick-section components) (Nicol, 2013).

11.3.2 USA

There have been no specific proposals for double-reheat AUSC PCC plant in the USA. However, Babcock & Wilcox have modified the design for an existing USC tower boiler, with technology from two-pass boilers, to create an AUSC tower boiler with improved reheat control and shorter pipework, which could be used with double-reheat systems. Babcock & Wilcox are working with turbine manufacturer Toshiba on alternative boiler-turbine configurations to minimise piping length (Nicol, 2013).

11.3.3 Japan

The Japanese programme has generated sufficient information to create a P&ID for a double-reheat AUSC PCC plant, shown in Figure 35, with a detailed list of candidate materials for critical components. There are plans in Japan to build a 600 MW FSDP from 2017 to 2021. The Japanese FSDP has the following steam parameters 700°C/720°C/720°C/35 MPa, reaching 46–50% electrical efficiency (net, LHV). Operation and feedback would be from 2021 to 2026 (Nicol, 2013).

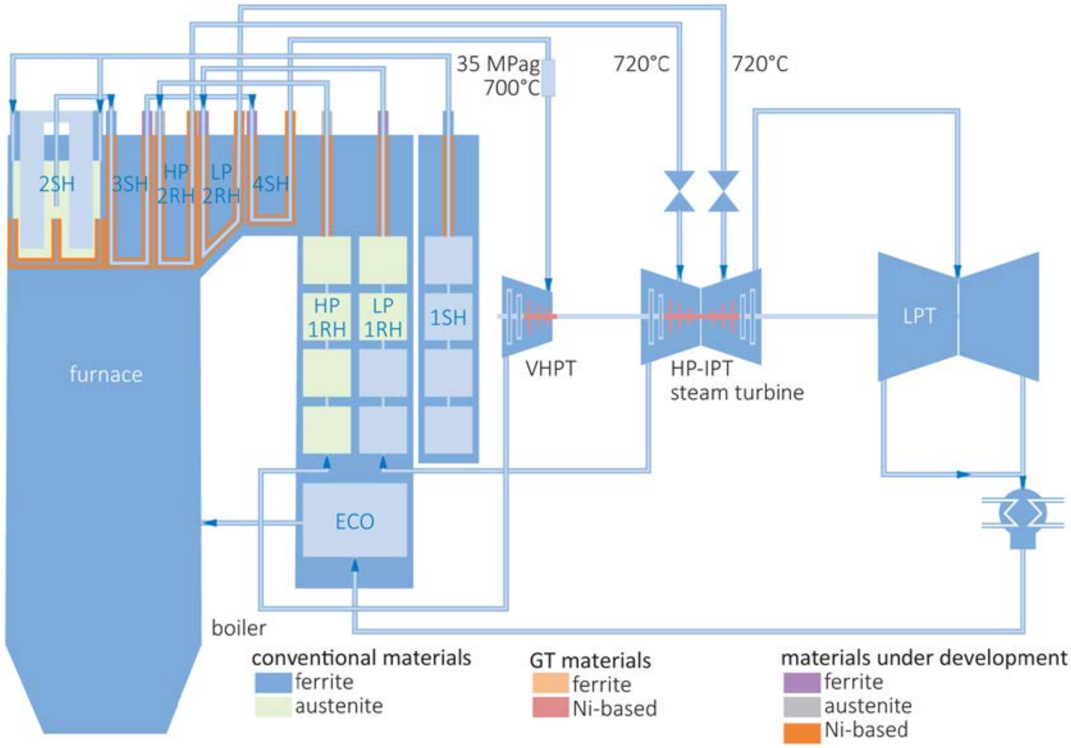

Figure 35 Flow diagram of a Japanese double-reheat AUSC PCC plant (Fukuda, 2012a)

11.3.4 China

In China, double-reheat AUSC technology is under investigation, but not for the FSDP (Nicol, 2013). Such plant would employ the CCHLPA technology, as described earlier, to minimise the amount of pipework. AUSC double-reheat units with steam parameters of 700°C/720°C/720°C/35 MPa could reach 52% net electrical efficiency (LHV), or 236 g/kWh, in Shanghai (Feng, 2014b).

11.3.5 Siemens

Figure 36 shows historic and projected steam cycle efficiencies for single and double-reheat turbines for USC and AUSC steam conditions (Quinkertz, 2014). Siemens say that their current double-reheat turbines can reach 48.8% net electrical efficiency (LHV), which should be demonstrated at Waigaoqiao No 3 unit 9 in 2017. Applying AUSC technology to Waigaoqiao No 3 unit 9 would allow such efficiency to reach 52%. This figure shows the potential for AUSC to reach 54%.

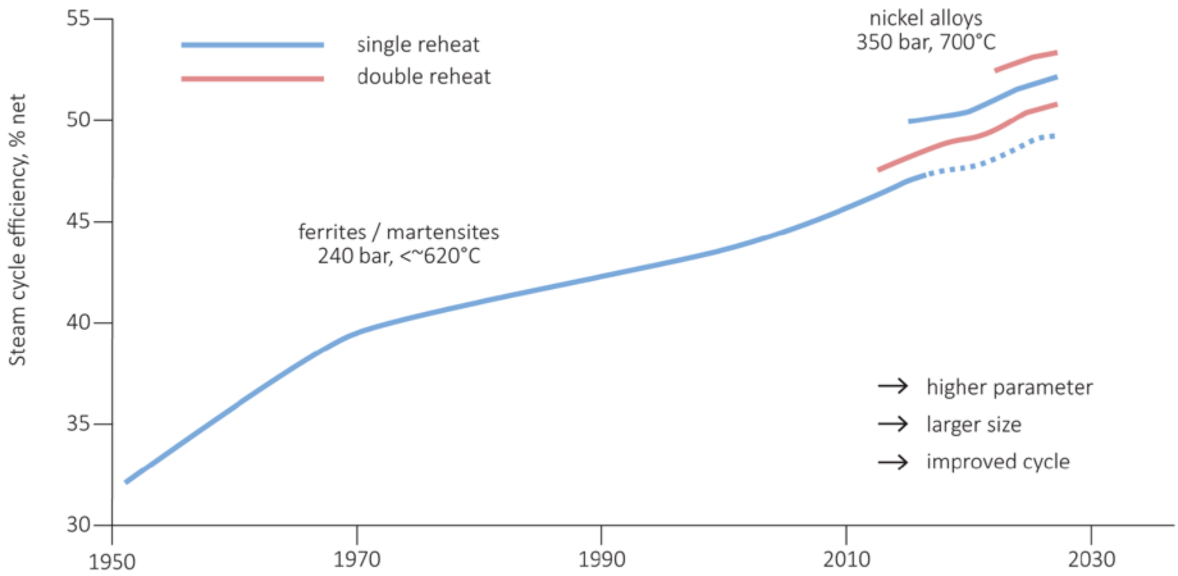

Figure 36 Progression of steam cycle efficiency in Siemens turbines (Quinkertz, 2014)

11.4 Process economics

The economic viability of AUSC technology depends on the efficiency of such units, coal price, carbon tax and the capital cost. The capital cost is high for AUSC technology, as nickel alloys are expensive, due to high use of elements such as nickel, cobalt and molybdenum, and a unique manufacturing supply chain. Although the capital cost is greater, the fuel costs are reduced with the increased electrical efficiency. The superheater temperature of 700°C was chosen in the 1990s, as nickel alloys are technically capable of operating at this temperature and the resulting electrical efficiency of roughly 50% was thought to make such technology economically viable.

Mao (2012) presents the costs of USC and AUSC technology. He shows that, on a per tonne basis, Inconel 615 (473,000 US$/tonne) is 43 times more expensive than P91 (11,041 US$/tonne) and eight times more expensive than P92 (11,041 US$/tonne). Mao (2012) shows that in China, the capital cost for two 1000 MWe 600°C USC units with single-reheat is RMB 8 billion (US$1.27 billion), in which the superheat and reheat piping cost was 400 million RMB (US$ 63 million); accounting for 15% of total cost. However, for two 1000 MWe 700°C AUSC units with double-reheat, the cost for boiler tubing alone would be at least RMB 2.5 billion (US$380 million). In this case, the projected increase in electrical efficiency with AUSC technology is not considered sufficient to compensate for the high cost of nickel alloys, which renders AUSC technology economically unfavourable.

Gierschner and others (2012) say that components manufactured from nickel alloys are at least ten times more expensive than ferritic steel and five times more expensive than martensitic steel. Wheeldon and Shingledecker (2013) say that nickel alloys are anywhere from five to fifty times more expensive than steels used in USC technology. Due to the considerable cost of nickel alloys, new 650°C steels are in development to reduce the amount of nickel alloys used in AUSC plant, see Nicol (2014) for more information. As shown above, the costs estimates for AUSC technology vary widely and can only be confirmed with a commercial-scale demonstration unit.

11.5 All units

Figure 37 shows a scatter graph of the efficiency and unit size of all double-reheat units, operating, decommissioned, under construction and planned. For coal-fired double-reheat units, the electrical efficiency increased from 27% to 47.94% (net, LHV) in early 2015 and the unit size has increased from 100 to 1000 MWe.

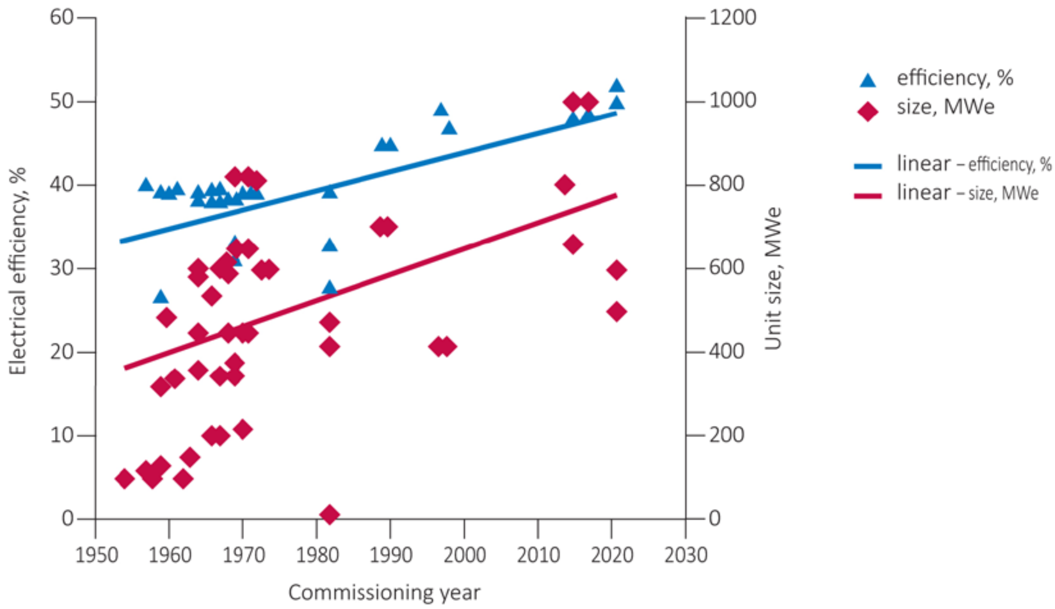

Figure 37 Efficiency and unit size of all double-reheat units, operating, decommissioned, under construction and planned (Platts, 2014; IEA CCC, 2012)

12 Conclusions

Double-reheat units emerged with the introduction of supercritical units in the 1950s. Most double-reheat units were built around the 1960s and 1970s in Germany, the USA and Japan. Double-reheat technology peaked with Nordjylland unit 3, reaching ultra-supercritical (USC) steam conditions of 582°C/580°C/580°C/29 MPa, setting a world record in electrical efficiency at 47.2% (net, LHV) in 1998. No other double-reheat units were built in the 16 years to 2015. As of July 2015, a total of 60 double-reheat units were built globally; amounting to 27.9 GWe. Of these units, 37 are coal-fired, amounting to 17.7 GWe, making up less than 0.5% of the total global fleet of pulverised coal combustion (PCC) power units. Over 94% of the boilers and turbines were manufactured in the country they were installed in. The boiler and turbine companies in the USA exported components overseas.

Initially, double-reheat units suffered from operational problems, high maintenance costs and low availability associated with the use of new austenitic steels (at the time) at ultra-supercritical steam conditions with superheat steam up to 649°C and 34.5 MPa. Such operational problems were unrelated to the number of reheats and were resolved by de-rating the superheat steam to 565°C and 25 MPa, or lower. Since then, the technical performance of double-reheat units has been comparable to single-reheat units. Compared to single-reheat units, double-reheat units increase electrical efficiency increase by 0.8 to 2% points (net, LHV), and the operational and maintenance (O&M) costs are similar. Therefore, double-reheat technology can be considered as proven with low technical and economic risks.

Double-reheat units fell out of favour in the 1970s largely due to the introduction of nuclear power, combined cycle gas turbines, and persistently low oil prices. The majority of existing double-reheat units will be decommissioned over the next few years, largely due to end of life and the introduction of more stringent emission regulations. Double-reheat units have had a lifetimes of up to 53 years long.

Rapid growth in the Chinese economy and its increased demand for electricity has led to the planned commissioning of 10 GWe of USC double-reheat units in 2015 alone. Double-reheat technology was identified as a key R&D project for China's 'Twelfth Five-year Plan (2011-2015)'. As of May 2015, Guodian Taizhou power plant has two double-reheat units with USC steam conditions of 600°C/620°C/620°C/29 MPa, which are the largest double-reheat units in the world at 1000 MWe each and set a new world record in electrical efficiency at 47.94% (net, LHV). This means that from 1959 to 2015, for coal-fired double-reheat units, the electrical efficiency increased from 27% to 47.94% (net, LHV) and the unit size has increased from 100 MWe to 1000 MWe.

The plant engineers at DONG Energy, who designed the double-reheat units in Denmark, devised and patented the Master Cycle in 2010. The Master Cycle modifies the steam cycle by adding a small turbine module, separate to the main turbine, which replaces a boiler feed pump (BFP) and reduces the size and amount of high temperature components. Compared to a conventional double-reheat cycle, calculations for the Master Cycle show an increase in electrical efficiency of 0.5% and a reduction in overnight specific investment costs (€/kW) over a conventional double-reheat cycle of 12–19%, which brings the costs equivalent to those of a single-reheat cycle. Since 2010, the Echelon Cycle proposed by Shanghai Turbine Works and the Regenerative Turbine proposed by the North China Electric Power University, use similar concepts to the Master Cycle. The Regenerative Turbine could result in net electrical efficiencies of 48.94–49.94% with a payback period for the unit at just under four years. Shanghai Turbine Works plan to demonstrate their Echelon cycle in 2017.

Improved plant configuration to reduce the length of pipework can increase unit efficiency and reduce capital costs. For example, cross compound at high/low position arrangement (CCHLPA), mounts the higher pressure steam turbine modules at the same level as the boiler steam header outlets, which reduces steam pipework lengths. Waigaoqiao No 3 unit 9 plans to be the first unit to use CCHLPA, along with other process improvements. It is expected to be commissioned in 2017 and should reach 48.92% net electrical efficiency (LHV) in Shanghai. With access to cooling water at an average of 10°C, this figure is estimated to be 51%.

Advanced ultra-supercritical (AUSC) technology, which uses nickel alloy components to achieve higher steam temperatures, is projected to become commercial in the early 2030s. A 600 MWe demonstration unit, using double-reheat at steam conditions 700°C/720°C/720°C/35 MPa achieving up to 50% net electrical efficiency (LHV), should be operational in Japan in 2021. From 2031, commercial AUSC double-reheat units are expected to reach 54% net electrical efficiency (LHV).

Double-reheat technology is a proven technology for high efficiency and low emissions (HELE) power generation. When designing a new a pulverised coal fired power plant, the decision to opt for double or single-reheat is based on an economic trade-off between capital cost and fuel cost. The forecasted fuel costs will determine the payback period. Normally, fuel costs increase in the long-term. The capital, operational and maintenance costs are largely related to the labour costs, and the costs of concrete and steel. Generally, such costs in developed countries are double those in developing countries. When double-reheat units were built in Europe, the USA and Japan in the 1960s and 1970s, such costs would have been lower, thus favouring the process economics of double-reheat plant. Additionally, rising concern of climate change is leading to costs associated with emitting carbon dioxide, such as a carbon trading price or carbon tax. These costs should be accounted for, as they favour double over single-reheat.

Due to a combination of low labour costs, high fuel prices and increased demand for electricity, double-reheat units may be favoured in developing countries such as China and those in South-east Asia. Presently in China, low labour costs and high fuel costs result in a payback period for the incremental capital costs of a double-reheat cycle, over a single-reheat cycle, of just 6.25 years. In the developed countries, new build coal-fired power plant are scarce due to high capital costs, low electricity demand, stringent emission regulations, public opposition against coal power, the need for carbon capture and storage (CCS) and rising electricity generation from renewable sources.

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