Chapter 2

Comparison of Technologies

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CHAPTER 2
Comparison of Technologies

2-1. Higher Efficiency of Coal-fired Power Plants

Coal-fired power generation is achieved by coal combustion through a boiler, heating high-pressure water in a heat-transfer pipe by high-temperature combustion gas to produce steam that runs a turbine. The principle of thermodynamics states that power-generation efficiency becomes higher as steam temperature and steam pressure increase. How high-temperature, high-pressure steam is utilised to generate power is key to higher power-generation efficiency. Once it boils, water changes into steam. As pressure gets higher, the boiling point also increases. Once pressure reaches a critical point (374ºC, 22.1 MPa), water is turned into a supercritical fluid without boiling. A power-generation system utilising a boiling phenomenon at a temperature lower than the critical point is called a subcritical pressure unit, and another utilising the conditions exceeding the critical point is called a supercritical (SC) pressure unit; the latter system ensures higher efficiency. A system which further increases the steam temperature and pressure to over 600ºC is called an ultra supercritical (USC) pressure unit; it currently realises the highest power-generation efficiency in power generation by pulverised coal firing. Realising this USC pressure power-generation plant requires steel pipes for boilers to resist inner steam oxidation and outer high-temperature corrosion, in addition to having high-temperature strength. Nippon Steel & Sumitomo Metal has developed the 'new 18 percent chromium contained steel' and 'new 25 percent chromium contained steel' considered as having the world's highest strength and available as the world's first steel pipes for boilers, thus greatly contributing to realisation of the USC pressure power-generation plant. These steel pipes have now become the global standard and account for 80 percent of global market share. To further enhance the thermal efficiency of coal-fired power generation, the development of advanced USC technology is being promoted with the end view of its practical use around 2020.

Targeting higher efficiency, the development of integrated coal gasification combined cycle (IGCC) is being promoted. This cycle converts coal at a gasification furnace into synthetic gas consisting of carbon monoxide (CO) and hydrogen (H_2). The gas is combusted as a fuel for a gas turbine which generates power and, at the same time, discharges high-temperature exhaust gas to a heat-recovery steam generator to produce steam so as to generate power through a steam turbine as well. As a double power-generation system combining gas and steam turbines, IGCC can realise power-generation efficiency that is more than five percent higher than conventional coal-fired power generation. IGCC has been commercially operated in Europe and the United States (US); its commercial operation started in Japan in 2013. IGCC mainly features availability of low-grade coal with a low ash-melting point (brown coal), which is not easily available for conventional pulverised coal-fired power generation. Global reserves of brown coal are huge and its price is lower than bituminous coal. If IGCC spreads accordingly, the cost of coal-fired power generation is expected to be reduced.

IGCC is designed to gasify coal and generate power by utilising gas and steam turbines. Under study is the integrated coal gasification fuel cell combined cycle (IGFC) which, with the addition of fuel cell to the cycle, creates triple cycle power generation. Its power-generation efficiency is 55 percent (sending end

[2], HHV[3]), and, thus far, more than 15 percent higher in efficiency than coal-fired power generation. The fuel cell is key to this system and utilisation of solid oxide fuel cell (SOFC) is assumed. Small SOFCs have been commercialised for household use, but large SOFCs with high power generation for industrial use have yet to be put into practical use. The realisation of this system will lead to super-high-efficiency coal-fired power generation capable of greatly reducing greenhouse gas.

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[2] Refers to output at the power plant outlet. Because part of the generated electric power (sending end: gross) is used for running various internal facilities of the power plant, output at the power plant outlet (sending end: net) is slightly reduced.

[3] HHV = High heat value. Also called gross calorific value, its value is higher than the low heat value (LHV) or net calorific value by contained latent heat (heat of condensation) of steam. For this reason, power-generation efficiency by HHV standards is lower than that by LHV standards.

Figure 2.1: IGCC System Configuration

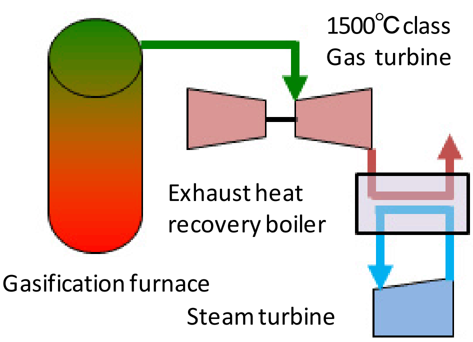
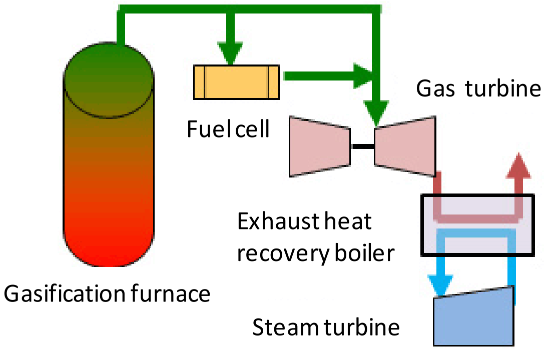
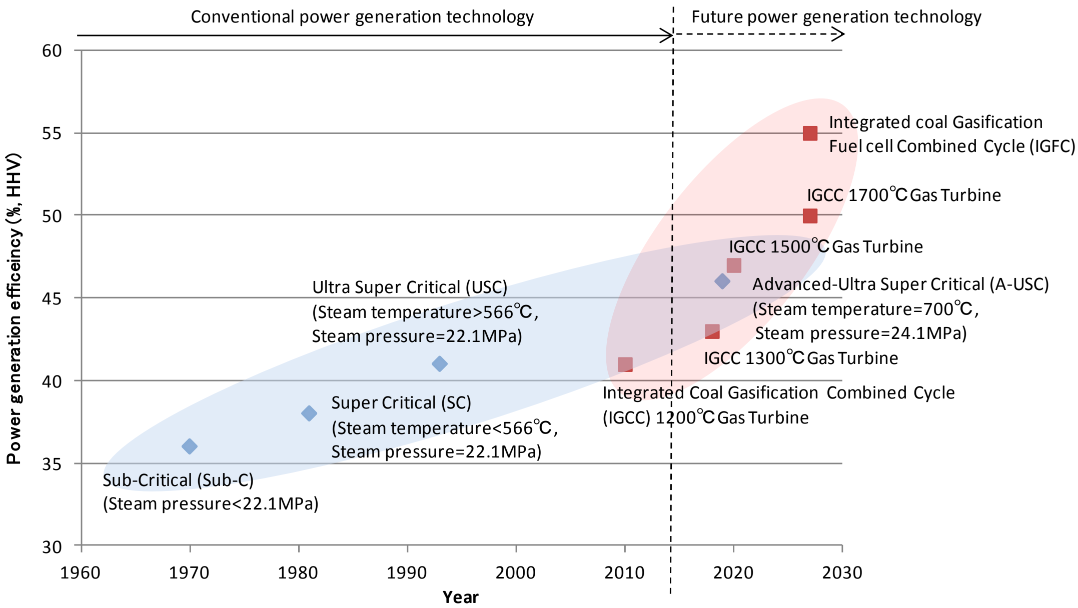


Figure 2.2: IGFC System Configuration



IGCC = integrated coal gasification combined cycle, IGFC = integrated coal gasification fuel cell combined cycle.
Source: Japan Coal Energy Center.

Figure 2.3: History of Efficiency Improvements in Coal-fired Power Plants



CPP = coal-fired power plant, HHV = high heat value.
Source: Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy, 13th Fundamental Issues Committee Materials.

2-2. Thermal Efficiency of Coal-fired Power Plants

Table 2.1 shows examples of the thermal efficiency of CPPs currently operating in the world. The highest power-generation efficiency is 45 percent to 46 percent (generating end LHV). Bituminous coal and brown coal are used, but the plants using bituminous coal tend to have higher power-generation efficiency by several points.

Table 2.1: Thermal Efficiency of Up-to-Date Coal-fired Power Plants (Global)

Area	Country	Technology	Coal type	Generation capacity（MW）	Gross thermal efficiency (% LHV)
North America	Mexico	Sub Critical (Sub-C)	Bituminous	1312	40
	USA	Sub Critical (Sub-C)	Bituminous	600	39
	USA (EPRI)	Super critical (SC)	Bituminous	750	41
Europe	Belgium	Super critical (SC)	Bituminous	750	45
		Super critical (SC)	Bituminous	1100	45
	Czechoslovakia	Sub Critical (Sub-C)	Lignite	600	43
		Sub Critical (Sub-C)	Lignite	300	42
	Germany	Super critical (SC)	Bituminous	800	46
		Super critical (SC)	Lignite	1050	45
	Netherlands	Ultra Super critical (USC)	Bituminous	780	46
	Slovakia	Super critical (SC)	Lignite	300	40
	Euroelectric	Super critical (SC)	Bituminous	760	45
		Super critical (SC)	Lignite	760	43
Asia pacific OECD	Australia	Super critical (SC)	Bituminous	690	39
		Super critical (SC)	Bituminous	698	41
		Ultra Super critical (USC)	Bituminous	555	41
		Ultra Super critical (USC)	Bituminous	561	43
		Super critical (SC)	Lignite	686	31
		Super critical (SC)	Lignite	694	33
		Ultra Super critical (USC)	Lignite	552	33
		Ultra Super critical (USC)	Lignite	558	35
	Japan	Sub Critical (Sub-C)	Bituminous	800	41
		Super critical (SC)	Bituminous	500 class	44.5
		Ultra Super critical (USC)	Bituminous	600 class	44
		Ultra Super critical (USC)	Bituminous	700 class	44.5
		Ultra Super critical (USC)	Bituminous	900—1000 class	45
	Republic of Korea	Sub Critical (Sub-C)	Bituminous	767	41
		Sub Critical (Sub-C)	Bituminous	961	42

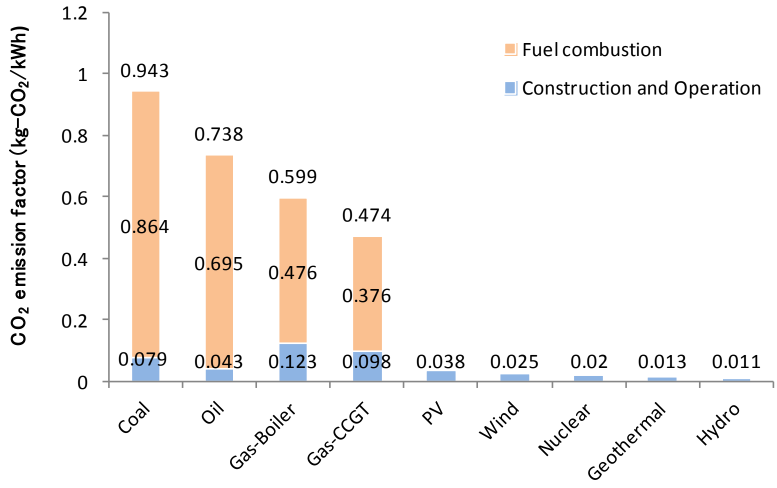
EPRI = Electric Power Research Institute, LHV = low heat value, MW = megawatt, OECD = Organisation for Economic Co-operation and Development, CPP = coal-fired power plant, USA = United States of America.
Sources: International Energy Agency, *Projected Cost of Generating Electricity,* 2010 edition; Ministry of Environment, Government of Japan.

2-3. CO_2 Emissions of Coal-fired Power Plants

Figure 2.4 compares CO_2 emissions, in Japan, of coal-fired power generation with power-generation technologies using petroleum, natural gas, nuclear power, and renewable energy. The life-cycle CO_2-emission factor of CPPs is 0.943kg-CO_2/kWh, the highest among different power-generation systems; it is more than two times higher than natural gas combined cycle power generation. Japanese CPPs have been using subcritical pressure (Sub-C) and supercritical pressure (SC) power-generation systems. With the recent replacement of Japan's CPPs, however, the USC power-generation system has been introduced in many cases, improving the CO_2-emission factor of coal-fired power generation year after year. Compared with petroleum and liquefied natural gas, however,

CO_2 emissions per generated energy are still higher, requiring further improvement of the CO_2-emission factor.

Figure 2.4: Life-cycle CO_2-Emission Factor, by Technology

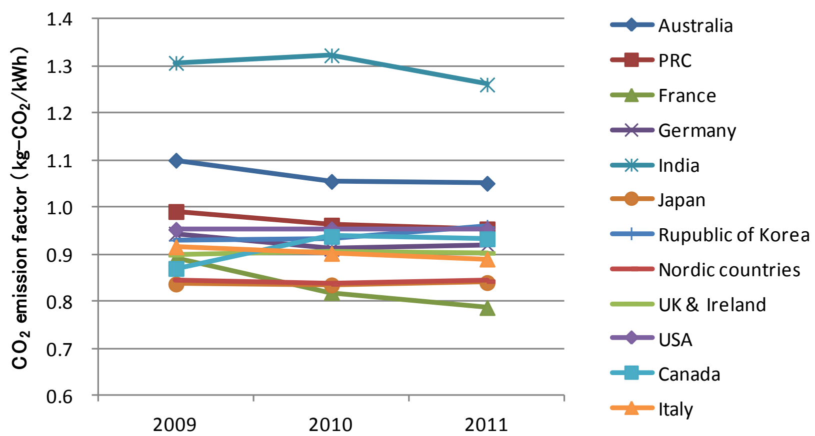


CCGT = combined cycle gas turbine, CO_2 = carbon dioxide, kWh = kilowatt-hour, PV = photovoltaics.
Source: Central Research Institute of Electric Power Industry, *Evaluation of Life-cycle CO_2 Emissions by Power Source,* 2010.

Figure 2.5 compares CO_2 emissions by coal-fired power generation in different countries. The CO_2 emission factors of CPPs differ greatly from one country to another, with India having the highest at 1.3kg-CO_2/kWh. Many relatively small CPPs operate in India, although their operating rate is low due to coal shortage and other factors. Also, the coal used has high ash content[4] and low design quality. These factors result in lower power-generation efficiency and higher CO_2 emission factor. The CO_2 emission factor in China, another coal-rich country comparable with India, is almost at par with those of the advanced countries. Previously, the CO_2 emission factor in China was as high as that in India. In recent years, the country has actively promoted replacement of its CPPs and introduced up-to-date coal-fired power-generation technology to successfully reduce the CO_2 emission factor. The CO_2 emission factor of CPPs is low in advanced countries, with those in Great Britain and Japan having the lowest.

[4] Because ashes are not combusted, higher ash content hinders combustion and lowers efficiency.

Figure 2.5: CO_2 Emission Factor of Coal-fired Power Plants, by Country



CO_2 = carbon dioxide, CPP = coal-fired power plant, kg = kilogram, kWh = kilowatt-hour, PRC = People's Republic of China, UK = United Kingdom, USA = United States of America.
Source: Ecofys, *International Comparison of Fossil-power Efficiency and CO_2 Intensity*, Update 2014, Table 35.

Table 2.3 shows prediction of CO_2 emission factor of future technologies. This table compares only the CO_2 emission factor associated with coal combustion, not life-cycle CO_2 emission factor. The CO_2 emission factor of the widely used subcritical (Sub-C) pressure-power generation was 0.95 kg-CO_2/kWh, but that of latest USC pressure-power generation has been improved to 0.83 kg-CO_2/kWh. If A-USC pressure-power generation is realised, the CO_2 emission factor is expected to be improved to 0.75 kg-CO_2/kWh. In IGCC, the CO_2 emission factor is expected to be improved to 0.75 kg-CO_2/kWh, equivalent to A-USC pressure-power generation. In IGFC, the CO_2 emission factor is estimated to be further improved to 0.63 kg-CO_2/kWh.

Both A-USC pressure-power generation and IGCC power generation are expected to be put to practical use around 2020, and IGFC around 2025, respectively.

Table 2.2: Prediction of CO_2 Emission Factor of Future Technologies

Technology type	CO_2 emission factor (kg-CO_2/kWh)	Net thermal efficiency (%, HHV)	Status
Sub Critical **(Sub-C)** (Steam pressure<22.1MPa)	0.95	36	Conventional technology
Ultra Super Critical **(USC)** (Steam temperature<566℃ Steam pressure=22.1MPa)	0.83	42	Latest technology
Advanced Ultra Super Critical **(A-USC)** (Steam temperature=700℃, Steam pressure=24.1MPa)	0.75	46	will be commercialized by 2020
Integrated coal Gasification Combined Cycle **(IGCC)**	0.75	46	will be commercialized by 2020
Integrated coal Gasification Fuel cell Combined Cycle **(IGFC)**	0.63	55	will be commercialized by 2025

CO2 = carbon dioxide, kWh = kilowatt-hour.
Sources: Created from Agency of Natural Resources and Energy*, Overview of Electric Power Source and Demand;* New Energy and Industry Technology Development Organization, *Technology Strategy Map 2009*; Report of the cost estimation and review committee.

2-4. Power-generation Cost of Coal-fired Power Plants

Evaluation of power-generation cost varies, depending on how preconditions are set. As a matter of course, power-generation costs differ not only from one country to another, but from one power plant to another even in the same country, if installation conditions are different. This section introduces some examples of typical cost calculations.

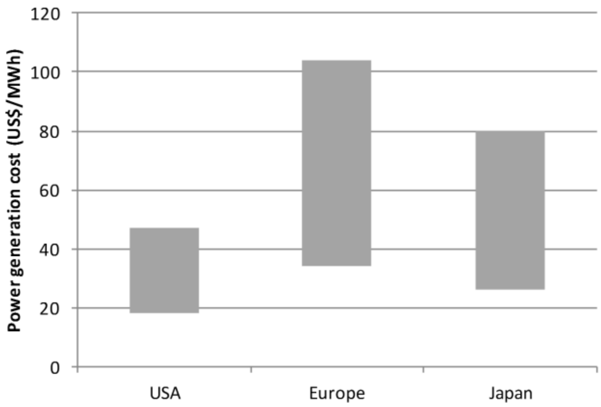
A. International Energy Agency, *World Energy Outlook 2013*

Figure 2.6 shows power-generation cost of existing CPPs according to the *IEA World Energy Outlook 2013.*

Power-generation cost is lowest in North America at approximately US$20–US$40/MWh, and approximately US$30–US$80/MWh in Japan and Europe. Many depreciated CPPs remain in North America as a result of newly constructed power plants being pulled back and/or replaced due to competition with natural-gas-fired power generation (mainly CCGT) in the 1990s, thereby reducing costs in the US. In the wholesale electric-power market in the US, more power plants are capable of gaining higher profits by generating power according to the prices of coal and natural gas; in short, a mechanism that allows high-cost power plants to lose in market competition and low-cost power plants to survive. As an example, when the Henry hub natural-gas price dropped to US$3/MMBtu or even lower due to the shale-gas revolution in North America, natural-gas-fired power generation became less expensive than coal-fired power generation, causing a shift to the former. But after the Henry hub natural-gas price rose to US$4.5–US$5/MMBtu, the competitiveness of CPPs was restored, allowing an increasing number of CPPs to operate again. Thus, the price of the Henry hub natural gas is a factor that decides operation of CPPs in the wholesale electric-power market in the US, and sets the upper limit of power-generation cost.

In Europe, on the other hand, the prices of natural gas and CO_2 emission credit serve as factors to decide operation of CPPs. A shift to CPPs is taking place in Europe due to the high price of natural gas and lagging CO_2 emission credit price. But since natural gas price in Europe is higher than in North America, however, the cost of power generation of CPPs is also relatively high.

Figure 2.6: Comparison of Costs of Coal-fired Power Generation (IEA)

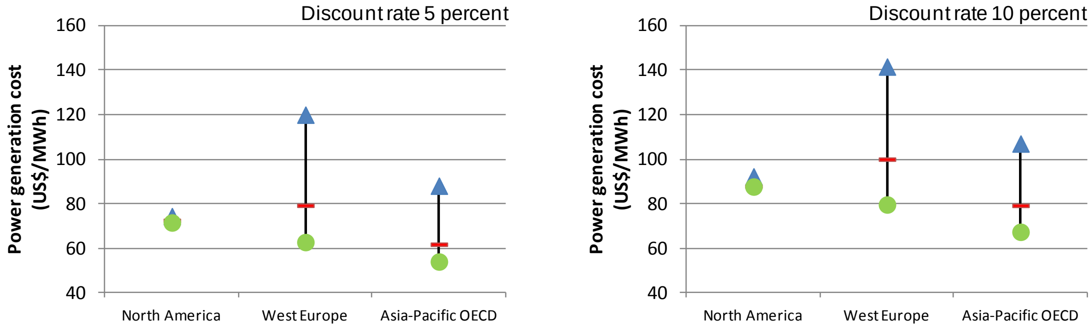


IEA = International Energy Agency, MWh = megawatt-hour, USA = United States of America.
Coal-fired power generation efficiency: 40 percent, Coal price index: US: Central Appalachian coal, Europe: ARA (Amsterdam-Rotterdam-Antwerp) coal, Japan: MCR (McClosky's Coal Report) Japanese market, CO_2 emission right cost included in the European power generation cost.
Source: International Energy Agency, *World Energy Outlook 2013.*

B. Organisation for Economic Co-operation and Development/Nuclear Energy Agency, *Projected Cost of Generating Electricity,* 2010 edition

The levelised cost of electricity or power-generation cost was calculated based on the cost data provided by experts in each country (Figure 2.7). In this calculation, the total life-time cost required for a specific coal-fired power generation project is discounted to the current value and equalised based on annual power generation. Discount rates of five percent and 10 percent are assumed. For a five-percent discount rate, the power generation cost is US$71.5–US$74.4/MWh for North America, US$62.7–US$120.0/MWh for Western Europe, and US$54.0–US$88.1/MWh for Asia and Pacific OECD countries. In case of a 10-percent discount rate, the power generation cost is US$87.7–US$92.3/MWh for North America, US$79.6–US$141.6/MWh for Western Europe, and US$67.3–US$107.0/MWh for Asia and Pacific OECD countries. In this test calculation, the width of power-generation cost is small in the US but large in Western Europe and Asia and Pacific OECD countries. Although this calculation assumes the CO_2 price to be US$30/$CO_2$, the setting of this price decides whether CCS should be introduced and changes the coal-fired power-generation cost. It is a big indefinite factor in calculating the power-generation cost.

Figure 2.7: Comparison of Costs of Coal-fired Power Generation (OECD/NEA)



MWh = megawatt-hour, NEA = Nuclear Energy Agency, OECD = Organisation for Economic Co-operation and Development.
Source: Organisation for Economic Co-operation and Development/Nuclear Energy Agency, *Projected Cost of Generating Electricity,* 2010 edition.

C. World Energy Council, *World Energy Perspective: Cost of Energy Technology*

Table 2.4 shows the World Energy Council's calculation results of levelised cost of electricity, or power-generation cost, of coal-fired power generation. This test calculation assumes a capital-cost discount rate of 10 percent. However, since it is pointed out that investors often ask for a discount rate of 18 percent or more to construct a new power plant, a further increase in the figures could be assumed. The economic efficiency of CPPs in Europe and Australia greatly depends on whether or not a carbon tax is imposed because this test calculation does not include it. For CPPs in PRC, the initial investment cost is as low as US$660,000/MW, or 80 percent of the global average. Even if coal from Australia is used, the power-generation cost would be US$35/MWh, less than half the cost in Europe and the

US.

Table 2.3: Comparison of Coal-fired Power-Generation Costs (WEC)

Area	CAPEX (million US$/MW)	OPEX (US$/MW/year)	Capacity utilization ratio (%)	LCOE (US$/MWh)
PRC	0.66-0.66	32,820-50,000	80	35-39
Australia	2.51-3.70	36,185-60,673	83	93-126
USA	2.94-3.11	29,670-32,820	80-85	77-78
UK	2.27-2.85	30,600-76,500	95-98	119-172

CAPEX = capital expenditure, LCOE = levelised cost of electricity, MW = megawatt, MWh = megawatt-hour, OPEX = operating expense, PRC = People’s Republic of China, UK = United Kingdom, USA = United States of America.
Source: World Energy Council, *World Energy Perspective: Cost of Energy Technology,* 2013.

D. Energy Information Administration, *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants,* April 2013

Table 2.4 shows an analytical example of power-generation cost in the US, according to EIA, and features evaluation of a wide range of power source types. The figures represent only a part of analysis which also covers nuclear power generation, hydroelectric power generation, and different kinds of renewable energy. It also evaluates maintenance costs as well as initial investment. It covers only the US but is useful material for cost comparison amongst power sources.

Table 2.4: Comparison of Costs of Thermal Power Generation (EIA)

	Plant Characteristics		Plant Costs (2012$)		
	Nominal Capacity (MW)	Heat Rate (Btu/kWh)	Overnight Capital Cost ($/kW)	Fixed O&M Cost ($/kW-yr)	Variable O&M Cost ($/MWh)
Coal					
Single Unit Advanced PC	650	8,800	$3,246	$37.80	$4.47
Single Unit Advanced PC with CCS	650	12,000	$5,227	$80.53	$9.51
Single Unit IGCC	600	8,700	$4,400	$62.25	$7.22
Single Unit IGCC with CCS	520	10,700	$6,599	$72.83	$8.45
Natural Gas					
Conventional CC	620	7,050	$917	$13.17	$3.60
Advanced CC	400	6,430	$1,023	$15.37	$3.27
Advanced CC with CCS	340	7,525	$2,095	$31.79	$6.78
Conventional CT	85	10,850	$973	$7.34	$15.45
Advanced CT	210	9,750	$676	$7.04	$10.37

Btu = British thermal unit, CCS = carbon capture and sequestration, CT = combustion turbine, EIA = Energy Information Administration, IGCC = integrated coal gasification combined cycle, kW = kilowatt, MW = megawatt, MWh = megawatt-hour, O&M = operation and maintenance, PC = pulverised combustion.
Source: Energy Information Administration, *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants,* April 2013.

E. Economic Research Institute for ASEAN and East Asia, *Study on the Strategic Usage of Coal in the EAS Region*

In a 2012 report, the Economic Research Institute for ASEAN and East Asia (ERIA) summarises the efficiency and power-generation cost of coal-fired power generation. The power-generation efficiency, initial investment cost, operating cost, power-generation cost, and CO_2 emissions obtained from actual plant data are described on three coal-fired power-generation systems: subcritical pressure (Sub-C) power generation, supercritical pressure (SC) power generation, and ultra supercritical pressure (USC) power generation.

The figures in Table 2.5 show higher initial investment amount for facilities with higher power-generation efficiency. This is because boiler tubes and other equipment use more expensive special materials capable of withstanding high temperature and high pressure, and more complicated heat-recovery facilities. Coal consumption, however, is lower in case of high-efficiency technology. Thus, if economic efficiency is evaluated over a certain period of a power plant's operation, the average cost becomes lower for higher-efficiency technology. As a matter of course, higher-efficiency technology emits less CO_2. This is significant as one may be captivated by the low initial investment and thus fail to properly evaluate the true economic efficiency of a power plant over its entire operation period.

Table 2.5: Power-Generation Efficiency and Costs of Different Coal-fired Power Plant Technologies (ERIA)

	Boiler Type		
	Ultra Super Critical (USC)	Super Critical (SC)	Sub-critical (Sub-C)
Thermal Efficiency (%, LHV)	41.5～45.0%	40.1～42.7%	37.4～40.7%
Initial Cost (million US$)	1,298 million US$	991～1,240 million US$	867～991 million US$
Fuel Consumption (ton/year)	2,229,000 tons/year (100%)	2,275,000 tons/year (+2.1%)	2,413,000 tons/year (+8.3%)
CO2 Emission (ton/year)	5,126,000 tons/year (100%)	5,231,000 tons/year (+2.11%)	5,549,000 tons/year (+8.3%)
O&M Cost (million US$/year)	3.42 million US$/year	4.1 million US$/year	5.0 million US$/year
Generation Cost (US$ cent/kWh)	4.03 cent/kWh (100%)	4.19 cent/kWh (+3.9%)	4.44 cent/kWh (+10.2%)
Examples	✓ "Isogo" J-POWER, Japan ✓ "Tachibanawan" J-POWER, Japan ✓ "Nordjylland" Vattenfall, Denmark ✓ "Xinchang" CPI, NSRD and J-Power, China	✓ "Takehara" J-POWER, Japan ✓ "Matsushima" J-POWER, Japan	✓ "Taichung" Taipower, Taiwan ✓ "Thai Binh" EVN, Vietnam

ERIA = Economic Research Institute for ASEAN and East Asia, LHV = lower heat value, CO2 = carbon dioxide, O&M = operation and maintenance, CPI = China Power Investment Corporation, NSRD = Shenzhen Nanshan Power Corporation, EVN = Viet Nam Electricity.
Source: Economic Research Institute for ASEAN and East Asia, *Study on the Strategic Usage of Coal in the EAS Region,* Research Project Report 2012, No. 27.