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Cost–Benefit Analysis of HELE and Subcritical Coal-Fired Electricity Generation Technologies in Southeast Asia

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Abstract: A large potential exists in the Southeast Asia region for deployment of high-efficiency, low-emission (HELE) electricity generation technologies. A cost–benefit analysis of HELE technologies compared to the less efficient subcritical electricity generation plants is thus carried out to find a persuasive scenario supporting quicker transition from subcritical stations towards HELE technologies in the region. A levelized cost of electricity (LCOE) analysis is carried out for both technologies under four potential policy scenarios. Scenario 1 does not take into consideration any carbon pricing or costs associated with the desulphurization (deSOx) and denitrification (deNOx) facilities. Scenario 2 (Scenario 3) incorporates carbon pricing (costs associated with the deSOx and deNOx facilities), and Scenario 4 includes both carbon pricing and costs associated with the deSOx and deNOx facilities. Under each scenario, a sensitivity analysis is performed to evaluate the uncertainty affecting the future coal prices. This study demonstrates that HELE technologies are competitive against the subcritical plants under all four scenarios and both the technologies derive benefit from lifetime extensions and low coal prices. It is revealed that future deployments of HELE technologies can be best expedited by factoring in carbon pricing in LCOE costs of coal-fired power plants under Scenario 2.

Keywords: high-efficiency; low-emission; carbon dioxide emissions; carbon pricing; subcritical; desulphurization; denitrification; cost–benefit analysis; levelized cost of electricity

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1. Introduction

Currently, coal-fired electricity generation plants with a total capacity of about 1700 GW account for over 41% of the electricity generation worldwide [1]. Coal-fired electricity generation is responsible for over 28% of global carbon dioxide (CO_2) emissions [2], and scientific studies suggest that CO_2 emissions are responsible for global warming and associated devastating public health and environmental impacts.

As the pressure to act against global warming is increasing, several coal-using countries have been working on their national plans to kick in global efforts to reduce CO_2 emissions from their electricity generation sectors through development and deployment of high-efficiency, low-emission (HELE) coal-fired and renewable energy (RE) power generation technologies. HELE technologies utilize higher temperatures and pressures, compared to less-efficient subcritical technologies [3,4]. HELE electricity generating plants include supercritical (SC), ultra-supercritical (USC), advanced ultra-supercritical (A-USC), integrated gasification combined cycle (IGCC) and integrated gasification fuel cell (IGFC) technologies developed to increase the efficiency of coal-fired electricity generation plants, and thus reducing CO_2 and other greenhouse gas (GHG) and non-GHG emissions. HELE units emit

25–33% less CO_2 than the global average CO_2 emissions from existing electricity generation fleets and up to 40% less than the oldest technologies [4]. Table 1 shows the efficiency ratings; CO_2 intensity factors; and fuel consumption values for subcritical, SC, USC and A-USC power plants.

Table 1. HELE technologies: Low heating value (LHV)-based efficiency improvements, intensity factors and fuel consumption [5].

	Efficiency Rate (% Net LHV Basis)	CO_2 Intensity	Coal Consumption	Steam Temperature
A-USC	45–50%	670–740 g CO_2/kWh	290–320 g/kWh	700 °C
USC	Up to 45%	740–800 g CO_2/kWh	320–340 g/kWh	600 °C
SC	Up to 42%	800–880 g CO_2/kWh	340–380 g/kWh	Approx. 550–600 °C
Subcritical	Up to 38%	≥880 g CO_2/kWh	≥380 g/kWh	<550 °C

Every 1% improvement in the efficiency of coal-fired electricity generation plants results in a 2–3% reduction in CO_2 emissions [6]. In this regard, since the year 2000, HELE power plants have already reduced global CO_2 emissions by over 1 billion tons [7]. HELE technology is a vital first step to the carbon capture and storage (CCS). The International Energy Agency (IEA) Energy Technology Perspective (ETP) 2012 2 °C Scenario (2DS) indicates that to limit the average rise in global temperature to 2 °C, it is necessary to cut more than half of the energy sector-related CO_2 emissions by 2050 (compared to 2009) [3]. Combined with CCS, HELE technologies are expected to cut global average CO_2 emissions from coal-fired plants by as much as 90% to attain the 2DS by 2050 [5].

Southeast Asia consists of ten countries of the Association of Southeast Asian Nations (ASEAN): Brunei Darussalam, Indonesia, Cambodia, Lao People's Democratic Republic (PDR), Singapore, Malaysia, Philippines, Myanmar, Vietnam, and Thailand. ASEAN member countries have set a broad set of policies to fast-track the development of renewable electricity generation capacity. The region is aiming to generate 23% of its primary energy from RE sources by 2025, compared to 9.4% in 2014 [8]. While this upward trend towards RE is continuing, the vast availability of coal reserves in the region and its lower cost has made coal the largest and preferred source for electricity generation. The IEA forecasts that installed coal-fired electricity generation capacity will increase to around 160 GW by 2040, making a large contribution to growth in generation capacity of the region [9]. Additionally, coal-fired generation will overtake natural gas by 2040 to become the largest source of power capacity. Furthermore, the IEA confirms that low emission coal will be the generation of choice in the region and will provide 40% of electricity generation by 2040. There is a regional understanding among ASEAN nations that growing use of coal will necessitate a HELE technology energy pathway supported with renewables.

The levelized cost of electricity (LCOE) is often cited as a convenient summary measure of the overall competitiveness of different electricity generating technologies [10]. To influence the type of technology that project developers select in ASEAN countries, several LCOE studies focusing on RE technologies have been conducted [11–20]. Veldhuis et al. in [11], focused their study on LCOE of off-grid photovoltaic (PV) systems required to electrify Indonesian rural households and showed that off-grid PV systems are 19% cheaper as compared to electricity generation with diesel generator sets in most rural parts of Indonesia. In [12], Talavera et al. conducted a worldwide economic feasibility analysis of High Concentrator PV (HCPV) systems through the LCOE estimation. Blum et el. in [13], investigated the LCOE of isolated renewable hybrid mini-grid systems in Indonesia. In [16], Januar compared the economic viability of a 20 MW solar thermal and PV power plant in Rogkop, Indonesia, using the LCOE approach. Lau et al. in [17], presented a detailed analysis of PV grid parity based on the calculation of PV LCOE for the residential sector in Malaysia. In [18], the Asian Development Bank (ADB) conducted an LCOE analysis for REs for the greater Mekong sub-region (GMS) countries: Cambodia, Lao PDR, Myanmar, Thailand, and Viet Nam. Huber et al. in [19] concluded that the most economical options for electricity generation in the ASEAN region are hydro, biomass and geothermal. The study in [20] analyses LCOE of selected RE technologies in several ASEAN countries, and advises necessary policies to reach a significant competitive edge for those selected RE technologies.

The study conducted by Phuangpornpitak and Kumar [21] provides an in-depth analysis of the renewable hybrid mini-grid systems with solar PV, wind, battery and diesel that have been installed in the national parks of Thailand. In [22], Keeley and Managi have assessed the economic viability of renewable hybrid mini-grid systems in Indonesia.

There is also some limited work on LCOE focused at coal technologies and comparison of coal technologies with other electricity generation technologies for the Southeast Asian region. A cost–benefit analysis of US, SC and subcritical plants is carried out by the Economic Research Institute for ASEAN and East Asia (ERIA) in [23]. The ERIA's study confirms that USC is generally competitive against SC and subcritical plants. Also, the World Coal Association (WCA) and ASEAN Centre for Energy (ACE) report (herein called WCA report) suggests that various coal-fueled electricity generation technologies are the lowest LCOE option available for mass deployment in Southeast Asia [4].

The ASEAN governments are promoting HELE technologies as a key step towards CO_2 mitigation. The ASEAN countries are thus making a transition from less efficient subcritical stations towards HELE coal-fueled facilities. Current research suggests that almost half of coal stations under construction or in development are expected to make use of advanced HELE coal-fired technology. The analysis also indicates that 23% of coal capacity currently under construction or in development is SC, while a further 29% of proposed projects have not finalized the technology choice [4]. HELE coal-fired technologies are more expensive to build than the subcritical technologies due to more expensive materials, complex boilers and precise control systems. High cost is a main restriction element for large-scale deployment of HELE technologies. By contrast, subcritical electricity generating plants have been traditionally preferred due to their lower upfront costs and shorter lead times. It is therefore highly likely that project developers end up accepting lower efficiency and poorer emission rates from subcritical coal-fired technology. On the other hand, to decarbonize the electricity sector by 2050 under 2DS, electricity generation from subcritical coal plants needs to be completely phased out by 2050 and following 2020, the more efficient CCS fitted HELE coal-fired plants are to be employed. The IEA thus recommends the implementation of national energy plans and policies to rapidly phase out construction and deployment of subcritical coal-fired plants [24]. Though the ASEAN is making a transition away from less efficient subcritical stations towards HELE coal-fueled facilities, current deployment progress is slow and subcritical units are still being deployed. Scope thus exists for necessary policy support to expedite transition from less efficient subcritical units to HELE units. The work in this paper is therefore aimed at demonstrating economic feasibility of HELE against subcritical, and finding a policy scenario that will result in the decline of subcritical coal-fired electricity generation even more rapidly, and shift new project investments towards being in favor of HELE technologies. This study is deemed important for ASEAN governments as a point of reference to formulate necessary policies and emission standards that expedite transition to HELE technologies, as well as to improve energy efficiency and reduce emissions.

This study is novel in the sense that we have included A-USC in this study, and under each scenario, a sensitivity analysis is performed to evaluate the uncertainty affecting the future coal prices on coal plants of a 20- and 25-year lifespan. Carbon pricing is an important policy tool to promote more energy-efficient, low-carbon technologies that emit less CO_2 emissions [25]. Due to rising concerns of air pollution from coal power stations, implementation of air pollution control technologies and regulations are crucial for sustainable development [26]. The study thus seeks to answer the question as to which one of these approaches can best help to expedite deployments of HELE technologies in

Southeast Asia or whether a mix of these approaches should be implemented. Based on the analysis of results, relevant policy recommendations are also discussed.

2. Methodology

2.1. LCOE

The LCOE represents the lifetime average cost of electricity as a constant unit price (in USD per megawatt-hour (USD/MWh) for a specific electricity generation project; it is a commonly used metric to assess overall competitiveness of different electricity generation projects. This mainstream technique is therefore used in our study.

The LCOE is calculated by dividing the project's overall expected lifetime costs (including construction, fuel, financing, maintenance, insurance, taxes and incentives) with the project's lifetime expected power output (MWh) [4,27–29]. As the value of the dollar today does not have the same economic value as the dollar in future, to properly add costs that occur at different points in time, they are converted into "present value" terms through the use of "discounting". The present values of all expense are thus divided by the present value of electricity generation to compute the LCOE as:

$$LCOE = \frac{\sum_{t=1}^{N} \frac{[I_t + M_t + F_t]}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}}, \quad (1)$$

where:

I_t = Capital expenditure in the year t associated with the construction of the plant;
M_t = Non-fuel operating and maintenance costs in year t;
F_t = Fuel price expenditures in the year t;
E_t = Net electricity production in MWh in the year t;
N = Economic lifetime in years;
t = Year of lifetime (1, 2, . . . , N); and
r = Discount rate or interest rate.

If the net output of the plant is constant over the life of the plant, and if the operating, maintenance and fuel costs are also constant, Equation (1) can be reduced to:

$$LCOE = \frac{CAPEX \times FCF + O\&M_{fixed}}{CF \times 8760} + O\&M_{variable} + \Pi_{fuel} \times HR, \quad (2)$$

where:

- FCF is the fixed charge factor. The factor turns capital costs into a uniform annual amount and is given by:

$$FCF = \frac{r(1+r)^N}{(1+r)^N - 1}. \quad (3)$$

- $CAPEX$ is the capital expenditure (USD/MW). There are no publicly available CAPEX data sets for ASEAN countries. For our analysis, these figures are therefore replaced with engineering, procurement and construction (EPC) costs, in which other costs may incur additionally, such as land cost, cost of any additional emission controls and other financing costs;
- $O\&M_{fixed}$ is the fixed operation and maintenance (O&M) cost (USD/MW);
- CF is the capacity factor. It is a fraction between 0 and 1 representing the total generation of a plant as proportion to its nameplate capacity;
- 8760 is the number of hours in a year;
- $O\&M_{variable}$ is variable O&M cost (USD/MW);
- Π_{fuel} is the fuel price (USD/GJ (USD/MMBtu)); and
- HR is the heat rate (GJ/MWh (MMBtu/MWh)).

In addition to emitting (contributing to climate change), coal-fired power plants are a major CO_2 source of air pollution tied to heart and lung diseases. The toxic pollutants arising from coal power plants include sulphur oxides (SOx), nitrogen oxides (NOx), as well as mercury (Hg) and particulate matter (PM). Studies confirm that these emissions severely impact human health [30]. Our analysis suggests that the correct interpretation of LCOE results of coal-fired plants are blurred by the fact that a cost–benefit analysis does not reflect costs on society, such as CO_2, SOx, NOx, etc. Since HELE power plants pollute less SOx, NOx and CO_2 into the atmosphere than subcritical designs, their emission abatement, denitrification (deNOx) and desulphurization (deSOx) facilities and climate costs are expected to be less as compared to the subcritical plants of the same capacity. From the perception of global and ASEAN action on climate change, there is a clear imperative to make coal power generation sustainable by shifting incremental coal generation capacity under carbon pricing to make coal power generation more sustainable. Additionally, to improve public acceptance of the coal plants in the ASEAN region, there is a need to raise emission standards for coal plants in the region to the equivalent levels of the Organization of Economic Co-operation and Development (OECD) countries [26]. Therefore, we examine the role of carbon pricing and emission control technologies in transition to HELE technologies under four potential policy scenarios in Southeast Asia.

The cost of coal-fired electricity generation is heavily contingent on coal price. Since the Asian benchmark of thermal coal prices has been growing, based on (2), sensitivity of LCOE generation values is thus analyzed to evaluate the impact of rising coal prices in Southeast Asia on subcritical, SC, USC and A-USC coal-fired units with life spans of 20 and 25 years, under each scenario.

2.2. Scenarios Description

2.2.1. Scenario 1 (Base Scenario)

This scenario represents the continuous trend of the electricity sector's development from the past, and thus assumes no future for carbon pricing and no controls over NOx and SOx emissions in Southeast Asia. The associated carbon costs and NOx and SOx emission reduction costs are thus not accounted, and an LCOE analysis is simply based on base plant EPC, O&M, fuel costs and financing costs.

2.2.2. Scenario 2 (Climate Change Mitigation Scenario)

Carbon pricing is a tangible and cost-effective way of reducing risks, costs and GHG emissions. It provides a mechanism to account for the environmental, social and economic costs of climate change. In some Southeast Asian countries, a carbon pricing mechanism is fully implemented. Other Southeast Asian countries have planned for carbon pricing and have started to include analyses on the impact of carbon pricing in the electricity mix, while the remaining countries have not yet considered carbon pricing. Carbon pricing approaches in the ASEAN are "country specific", and there is no uniform carbon price across the region due to wide income disparity and poverty in the region. Among the ASEAN member states, Myanmar is the poorest economy. The Energy Master Plan (EMP) of Myanmar (2016) considers sensitivity analyses, based on the inclusion of carbon prices of USD 10/ton and USD 15/ton, for the development of an optimum power strategy for the country under a least-cost plan [31]. This scenario represents a future situation whereby a carbon price for coal power plants is fully implemented in the ASEAN region. Under this scenario, we thus assume a low-end carbon price of USD 10/ton in the ASEAN region to include poor economies, as well as for the achievement of low emissions to help limit global mean temperature under the 2DS. It is expected that the adoption of a carbon price in Southeast Asia under this scenario will accelerate the deployment of HELE coal-fired power plants.

2.2.3. Scenario 3 (Pollution Control Scenario)

The ERIA study [26] suggests that minimizing the emission of air pollutants in ASEAN countries is a pre-condition for the future use of coal power plants and for moving gradually to meet the current emission standards for coal plants of the OECD countries. In this regard, this scenario is considered to reflect a future situation where a legislation could take the form of ASEAN agreements to limit SOx and NOx emissions, linked through a uniform emissions standard mechanism in the ASEAN region. This scenario thus adds the cost of deSOx and deNOx facilities to the respective coal-fired plants in our analysis. It is expected that strict pollution control technology requirements/adoption could add heavy financial costs to subcritical plants and thus help phase out generation from subcritical coal-fired electricity generation plants. The approach is expected to accelerate the deployment of HELE plants (all of which reduce NOx and SOx emissions in the ASEAN region).

2.2.4. Scenario 4 (Climate Change Mitigation and Pollution Control Scenario)

This potential policy scenario is a mix of Scenarios 2 and 3, and represents a situation whereby carbon price and strict emission controls are imposed on coal power plants in the ASEAN region. This scenario encourages both climate change mitigation and air pollution emission reduction efforts. Under this scenario, the costs of deSOx and NOx facilities and carbon pricing are thus integrated in the overall costs of coal-fired plants.

2.3. General Assumptions

ASEAN's preference for coal is to continue in the future as it remains the most economic source of long-term base-load generation. Collectively, large scale operational coal-fired electricity generation plants around the globe are key contributors to total emissions. We thus consider large coal plants that are connected to the grid to provide base load. High-efficiency coal-fired plants are typically large and fall in the range 600 MW to 1000 MW. Since 1000 MW plants are usually grid-connected to provide base load, the cost–benefit analysis was thus targeted at 1000 MW-capacity coal-fired plants. Base-load power plants typically have annual capacity factors (CFs) that exceed 75 percent, but are usually more likely to be 90–98% [32]. All coal plants were modelled with an assumed CF of 80%. The LCOE calculation is usually performed assuming ideal conditions; a CF of 80% is thus a moderate choice. Based on plant capacity and utilization rate, total annual generation was thus 7008 gigawatt-hours (GWh).

Within a project capital structure, a project may receive equity investment from a private equity firm or group of investors, with an insurance wrap from a development financial institute (DFI). The coal-fired plant life cycle is about 25–30 years, however, investors are likely looking for faster return/payback based on 20–25-year cash flow projections. Therefore, for this reason, the return cash flow is analyzed for 20 and 25 years of the expected lifetimes for each coal technology.

The efficiency figures listed in Table 1 are based on the low heating value (LHV) of the fuel and net output (LHV, net). Coal-fired station efficiencies based on the high heating value (HHV) are generally around 2% to 3% lower than those based on LHV efficiencies. We thus added three percentage points to the higher end LHV-based efficiencies in Table 1 to get HHV-based efficiencies for different coal-fired plants and associated heat rates (See Table 2).

Table 2. High heating value (HHV)-based coal-fired power plant efficiencies and heat rates.

	Efficiency Rate (% Net HHV Basis)	Heat Rate of Fuel (Btu/kWh) (HHV Basis)
A-USC	47%	7259.57 (Btu/kWh)
USC	42%	8123.81 (Btu/kWh)
SC	39%	8748.72 (Btu/kWh)
Subcritical	35%	9748.57 (Btu/kWh)

Coal has a calorific value of 4000 kcal/kg and emissions (adjusted from the Intergovernmental Panel on Climate Change (IPCC) default emission factors) of 1.43 kg-/kg-coal. The kWh generated from CO_2 per kg of coal was computed by dividing the coal heat content (in Btu per kg) with HR (in Btu per kWh). Coal requirements to generate one kWh of electricity (in kg-coal/kWh) were multiplied by the emission factor to obtain levelized kg CO_2 emissions per kWh.

The general assumptions for electricity generation plant specifications and coal composition are summarized in Table 3.

Table 3. General assumptions for cost benefit analysis.

		Values	Remarks
Plant	Capacity Operation Operation rate	1000 MW 20, 25 years 80%	For cash flow purposes
	Thermal efficiencies	47%(A-USC), 42% (USC), 39% (SC), 35%(subcritical)	HHV based values. A 3% decrease in thermal efficiency is assumed.
	Annual generation	7008 GWh	
Coal specifications	Heating value	4000 kcal/Kg or equivalently 1008.656 Btu/Kg	
	CO_2 emissions	1.43 kg-CO_2/kg coal	Based on IPCC 2006 default emission for stationary combustion in the energy sector [33].

2.4. Cost Assumptions and Methodologies

For the analysis in this paper, LCOE consists of base plant costs, deSOx and deNOx costs, financing costs and emission costs. Base plant costs are divided into EPC, O&M and fuel costs. Similarly, deSOx and deNOx costs consist of EPC, O&M and additional fuel costs (see Table 4).

Table 4. Levelized cost of electricity (LCOE) breakdown costs.

		Factors
LCOE	Base plant	EPC O&M Fuel cost
	deSOx deNOx	EPC O&M Additional fuel cost
	Financing	Internal Rate of Return (IRR)
	CO_2	Carbon

The cost assumption of EPC is adopted from [23]. The EPC cost consists of generator, turbine, boiler and auxiliary machine costs, construction costs and other management costs. The standard assumption is that all coal technologies pay equivalent connection costs and land costs. These costs are thus not taken into consideration.

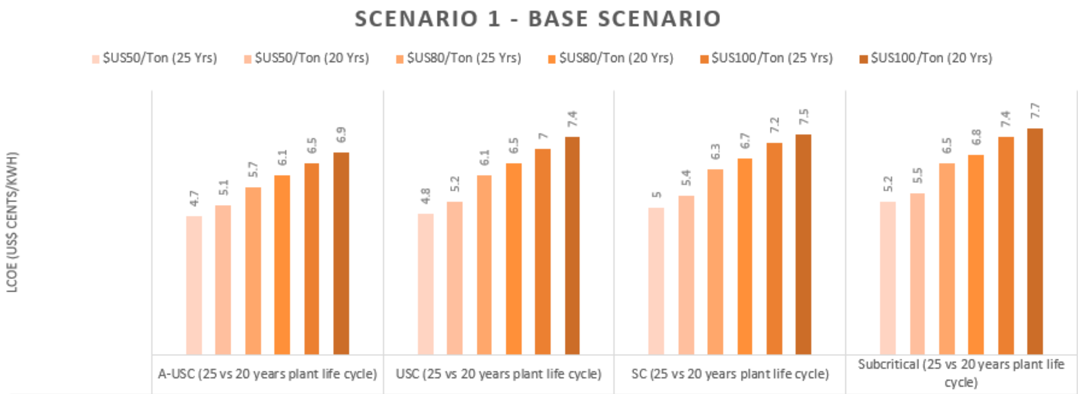
For the 25-year life cycle of the plant, the SC and subcritical capital costs are discounted from USC capital costs (USD 1931 million per 1000 MW), based on a cost index from [34]. Subcritical plant capital costs are indexed at 100, while SC and USC are indexed at 106.5 and 108.5, respectively. Based on these indexes, capital costs for SC are estimated at USD 1897 billion, and capital costs for subcritical are estimated at USD 1786 million. Likewise, the A-USC capital cost is an escalating cost index factor of 107.5. Therefore, the EPC costs of different types of coal combustion technologies are: A-USC at USD 2100 million, USC at USD 1931 million, SC at USD 1897, and subcritical at USD 1786. Additionally, for the cost assumption for the 20-year life cycle of the plant, the cost estimates for different types of coal-fired power generation technologies are: A-USC at USD 2625 million, USC at USD 2413.75 million, SC at USD 2371.25 million, and subcritical at USD 2232.5 million.

Base plant O&M costs are calculated by dividing non-fuel O&M costs by annual generation (7008 GWh). The annual costs for this analysis are calculated by applying O&M cost differences from [35] to the annual O&M costs for USC from [34]. Annual O&M costs are thus estimated at: USD 0.6/kWh for A-USC, USD 0.7/kWh for USC, USD 0.72/kWh for SC and USD 0.75/kWh for subcritical power plants.

Thermal coal prices grew since the second half of 2016 due to robust Chinese demand and supply tightness at several production sites [36]. For example, free on board (FOB) Kalimantan 4200 kcal/kg gross as received (GAR) coal price rose 34% since the start of 2017 to USD 49.60/mt in January 2018. Coal prices in April 2020 dipped to their lowest level since 2010 due to the COVID-19 pandemic. Import prices of the majority of ASEAN coal reserves have seen a strong momentum since mid-November 2020 and have been trending upward due to steady economic recovery and thus high demand of coal by key consumers in China, Japan, India and South Korea. Coal demand by importing countries is expected to rise in the post-COVID-19 era due to increased economic activities and, consequently, coal prices will evolve to new high prices in the future. To assess the impact of high coal prices on LCOE values, a bandwidth is thus analyzed to reflect the situation. The annual average fuel price assumptions used in this study were: USD 50/ton, USD 80/ton, and USD 100/ton. For the breakdown of these costs and calculation methodologies, the reader is advised to refer to [23].

3. Results

Figures 1–4 show the LCOE sensitivity analysis results in USD cents/kWh for Scenario 1 through 4, respectively. The results of Scenario 1 in Figure 1 suggest that HELE plants are competitive against subcritical plants without coal pricing and deSOx and deNOx costs. A comparison of the results of Scenario 1 through Scenario 4 in Figures 1–4, respectively, reveals that as carbon price and deSOx and deNOx costs are included, LCOEs increase. However, HELE plants retain their competitive edge over the subcritical plants. The study suggests that Scenario 1 offers the best economic case for HELE plants due to the lowest LCOE values for HELE plants, followed by the Scenario 3, Scenario 2 and Scenario 4.



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)	Subcritical (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	4.7	4.8	5	5.2
$US50/Ton (20 Yrs)	5.1	5.2	5.4	5.5
$US80/Ton (25 Yrs)	5.7	6.1	6.3	6.5
$US80/Ton (20 Yrs)	6.1	6.5	6.7	6.8
$US100/Ton (25 Yrs)	6.5	7	7.2	7.4
$US100/Ton (20 Yrs)	6.9	7.4	7.5	7.7

Figure 1. Scenario 1: Sensitivity Analysis of LCOE for different coal prices and economic life span of the subcritical and high-efficiency, low-emission (HELE) plants.

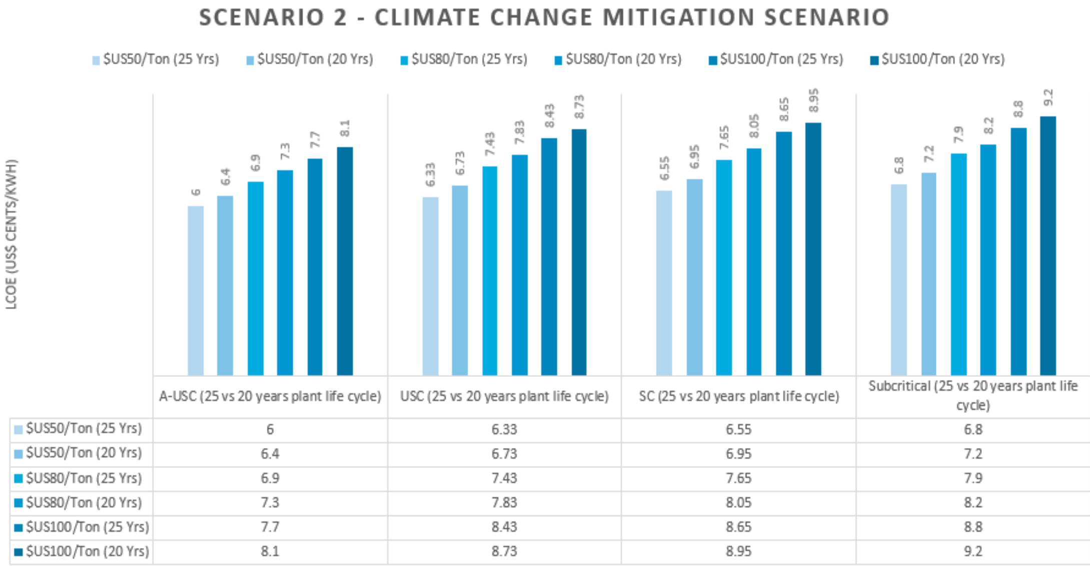


Figure 2. Scenario 2: Sensitivity Analysis of LCOE for different coal prices and economic life span of the subcritical and HELE plants.

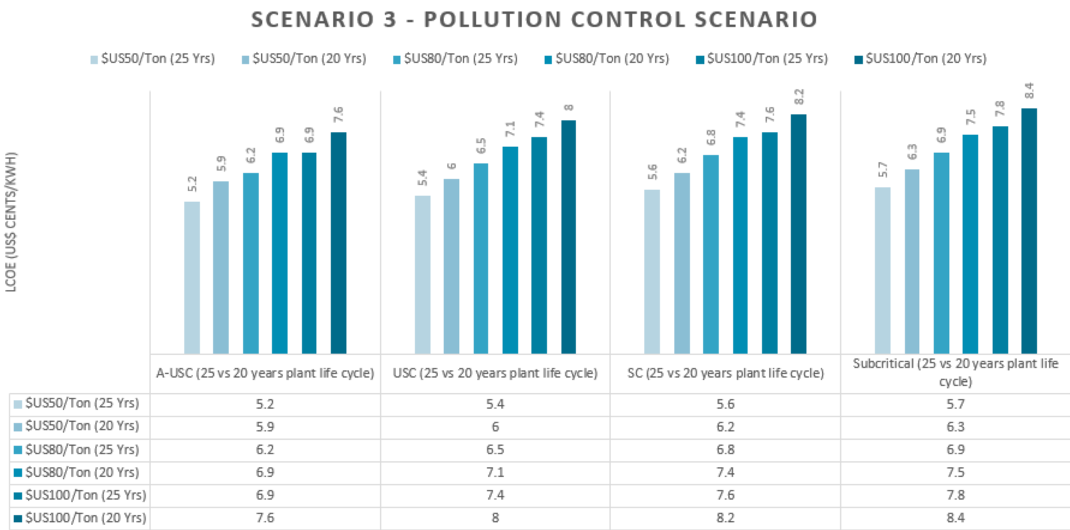
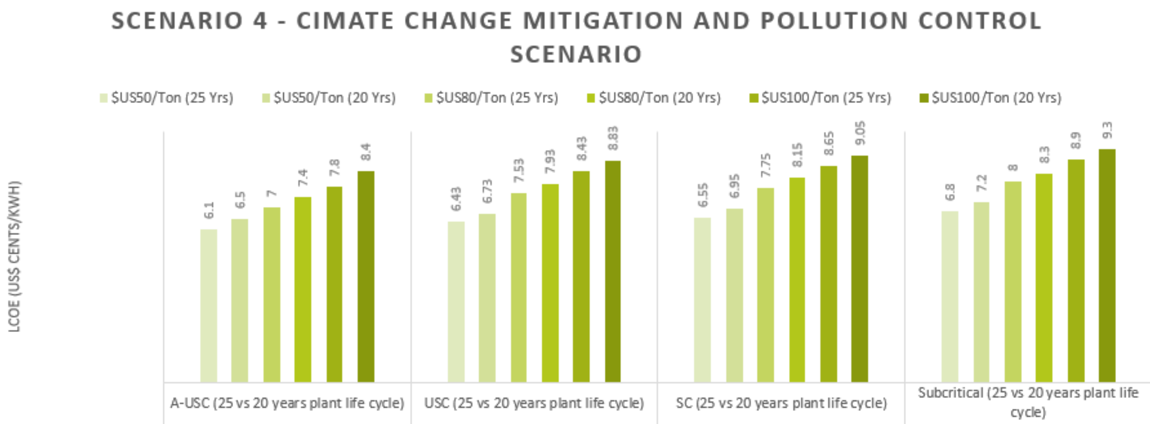


Figure 3. Scenario 3: Sensitivity Analysis of LCOE for different coal prices and economic life span of the subcritical and HELE plants.

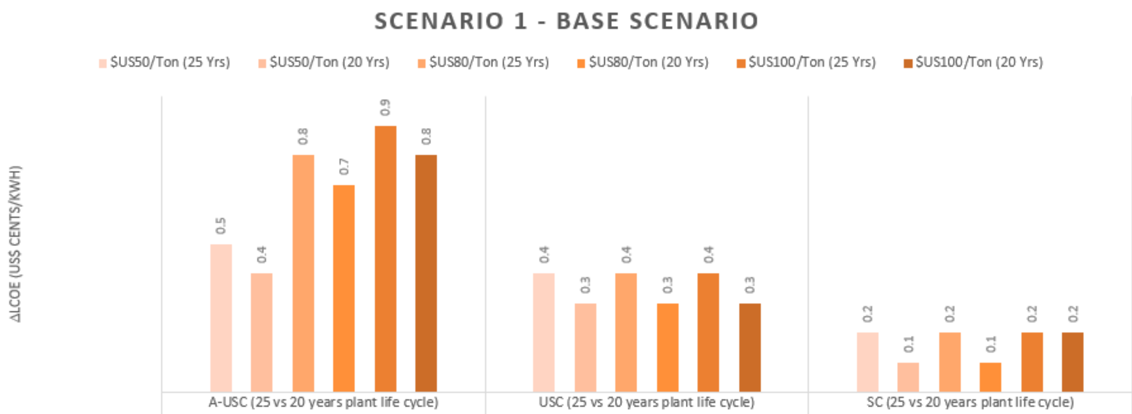
In all scenarios, for different coal prices and operating life spans of 20 and 25 years, both coal technologies derive benefit from lifetime extensions and low coal prices. However, HELE coal technologies derive more benefit due to lower LCOE values compared to the subcritical technology. It is immediately apparent that, in all scenarios, A-USC offers the best economic value, followed by USC and SC.

The lower LCOEs of HELE against the subcritical technology are necessary to shift investment decisions in favor of HELE and thus expedite deployment of HELE plants in the region. We thus evaluated the difference of LCOE values between HELE and subcritical technologies for each scenario using the LCOE difference metric $\Delta LCOE = |LCOE_{HELE} - LCOE_{Subcritical}|$. These differences are displayed in Figures 5–8, for Scenario 1 through 4, respectively. A close comparison of results in Figures 5–8 suggests that Scenario 2 is the best scenario causing the highest difference in LCOE values of subcritical and HELE plants. A similar observation reveals that Scenario 4 is the second-best Scenario, followed by Scenario 3. A closer analysis of results reveals that Scenarios 2 through 4 allow a shift of economics in favor of HELE technologies at the price of increased LCOE values of coal plants. However, notice that since Scenario 2 LCOE values are lower than the Scenario 4 LCOE values, Scenario 2 thus emerges as the best driver scenario to displace subcritical plants. Notice that Scenario 3 yields low LCOE prices as compared to the Scenario 4. However, as compared to Scenario 3, the difference in LCOE values of HELE and subcritical technologies in Scenario 4 is highly attractive to shift economics strongly in favor of HELE plants. Scenario 4 thus emerges as the second-best driver scenario. A similar comparison between LCOE values of coal plants, and LCOE difference in Scenario 1 and Scenario 3 suggests that Scenario 3 is the third-best Scenario.



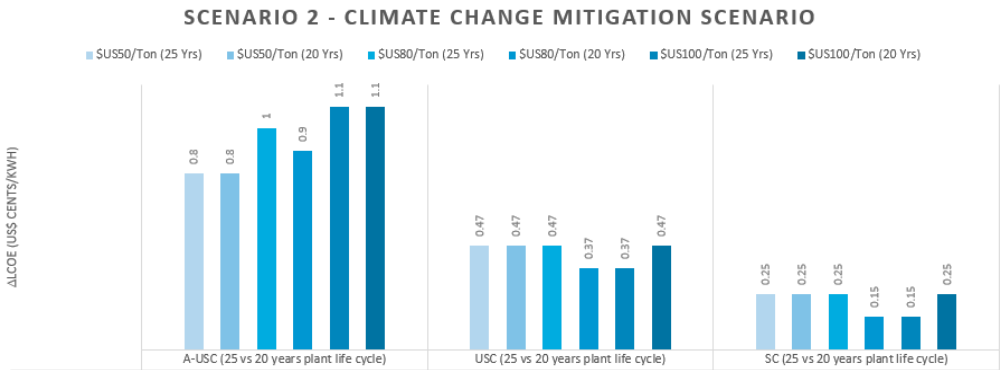
	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)	Subcritical (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	6.1	6.43	6.55	6.8
$US50/Ton (20 Yrs)	6.5	6.73	6.95	7.2
$US80/Ton (25 Yrs)	7	7.53	7.75	8
$US80/Ton (20 Yrs)	7.4	7.93	8.15	8.3
$US100/Ton (25 Yrs)	7.8	8.43	8.65	8.9
$US100/Ton (20 Yrs)	8.4	8.83	9.05	9.3

Figure 4. Scenario 4: Sensitivity Analysis of LCOE for different coal prices and economic life span of the subcritical and HELE plants.



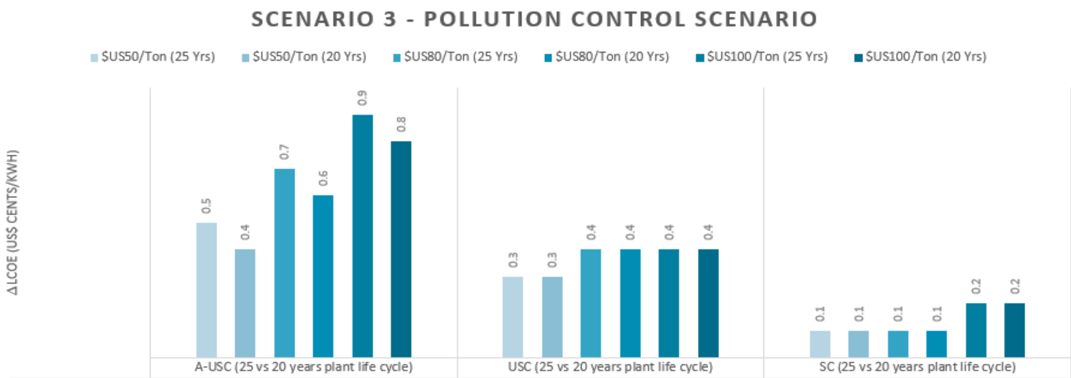
	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	0.5	0.4	0.2
$US50/Ton (20 Yrs)	0.4	0.3	0.1
$US80/Ton (25 Yrs)	0.8	0.4	0.2
$US80/Ton (20 Yrs)	0.7	0.3	0.1
$US100/Ton (25 Yrs)	0.9	0.4	0.2
$US100/Ton (20 Yrs)	0.8	0.3	0.2

Figure 5. Scenario 1: LCOE differences between HELE and subcritical technologies for different coal prices and economic life span of the plant.



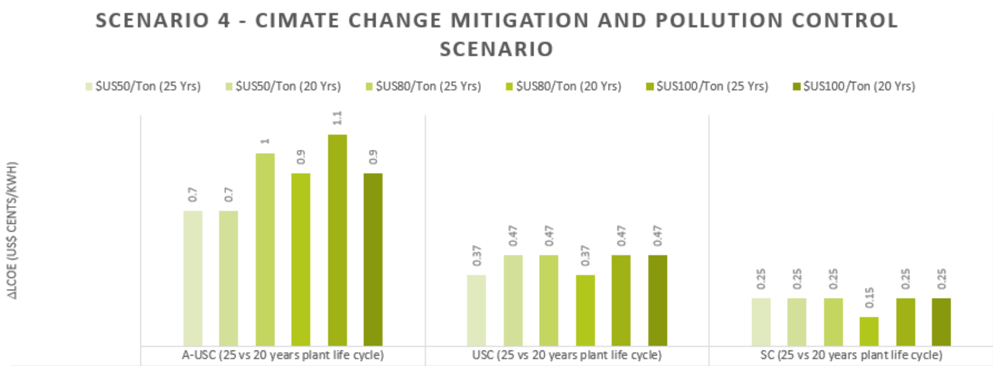
	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	0.8	0.47	0.25
$US50/Ton (20 Yrs)	0.8	0.47	0.25
$US80/Ton (25 Yrs)	1	0.47	0.25
$US80/Ton (20 Yrs)	0.9	0.37	0.15
$US100/Ton (25 Yrs)	1.1	0.37	0.15
$US100/Ton (20 Yrs)	1.1	0.47	0.25

Figure 6. Scenario 2: LCOE differences between HELE and subcritical technologies for different coal prices and economic life span of the plant.



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	0.5	0.3	0.1
$US50/Ton (20 Yrs)	0.4	0.3	0.1
$US80/Ton (25 Yrs)	0.7	0.4	0.1
$US80/Ton (20 Yrs)	0.6	0.4	0.1
$US100/Ton (25 Yrs)	0.9	0.4	0.2
$US100/Ton (20 Yrs)	0.8	0.4	0.2

Figure 7. Scenario 3: LCOE differences between HELE and subcritical technologies for different coal prices and economic life span of the plant.



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	0.7	0.37	0.25
$US50/Ton (20 Yrs)	0.7	0.47	0.25
$US80/Ton (25 Yrs)	1	0.47	0.25
$US80/Ton (20 Yrs)	0.9	0.37	0.15
$US100/Ton (25 Yrs)	1.1	0.47	0.25
$US100/Ton (20 Yrs)	0.9	0.47	0.25

Figure 8. Scenario 4: LCOE differences between HELE and subcritical technologies for different coal prices and economic life span of the plant.

4. Discussion, Policy Implications and Future Directions

The WCA report [4] confirms that advanced coal technologies have a slightly higher LCOE compared to subcritical coal due to the initial higher capital costs. In contrast, results obtained in our work suggest that HELE technologies are economically competitive against subcritical plants. Since the WCA study does not cover details of LCOE calculations, methodology, data, and assumptions, the LCOE results for coal technologies in our work are not directly comparable to the WCA's LCOE results for coal technologies. In our work, a sensitivity analysis was carried out to evaluate the impact of different coal prices for 1000 MW-capacity coal-fired plants with life spans of 20 and 25 years and relies on IEA-listed thermal efficiencies for both technologies under different potential scenarios from ERIA's study in [23]. Therefore, our work in this paper is also not comparable with the ERIA study in [23]. Both the WCA and ERIA studies do not include an economic feasibility study of A-USC for the Southeast Asia region. In contrast, in our work, A-USC emerges as the most economically attractive choice, followed by USC and SC for the region.

The ASEAN member states will continue to rely on coal use to meet the growing electricity demand in the foreseeable future due to the energy supply security, as well as the competitive LCOE from coal plants compared to the other power generation technologies. Our study suggests that HELE coal-fired power plants are economically competitive against subcritical plants. This competitiveness of HELE technologies is associated with levelized avoided costs associated with high efficiency (and thus fuel savings) and low emissions.

To meet the 2DS targets, policies and associated measures are needed to address both the long-term and short-term challenges linked with electricity generation from coal-fired plants. Following are the policy implications of our study:

- In the short term, the implementation of an efficient and impactful harmonized carbon pricing policy for coal-fired plants in all ASEAN countries is necessary to support the first-best driver, Scenario 2, to displace the subcritical plants and shift investments to emerging HELE opportunities in the ASEAN market. This would yield clean coal technology (CCT) for Southeast Asia and bring many benefits for the environment and people of the region.
- ASEAN countries have relatively lower emission standards of SOx, NOx and particulates when compared with OECD countries [23,37]. It is therefore very important to regulate continuation of coal through stringent environmental and emission standards to pave the way for HELE technologies. A long-term carbon policy coupled with emissions standards and effective enforcement is thus needed to support the second-best driver, Scenario 4, to shift the balance in favor of HELE plants. However, since the inclusion of a carbon price and raising emission standards causes a further rise in LCOE values, the ASEAN countries need to better understand how this move will affect the regional economic developments before it becomes an effective policy tool.
- In general, the clean use of fossil fuel will need to be accelerated in the policy agenda in ASEAN. Therefore, policy reform to accommodate clean fuels and technologies is urgently needed to ensure that clean use of fossil fuel will play a significant role for energy transition from a fossil fuel-based energy system towards a clean energy system where renewables and clean fuels play a major role in the future energy mix.

The cost of solar and wind technologies is also expected to drop in the future. In situations with strict emission control for coal-fired electricity generating plants (with carbon pricing and strict emission standards in place), switching from coal to these renewables would thus be expected. Nevertheless, the intermittent nature and low load factors associated with wind and PV technologies will likely limit their effectiveness in the region. In our future work, we aim to extend our cost–benefit analysis study by including solar and wind sources of energy generation in the ASEAN region. Financing costs also account for a considerable share of LCOE and the competitiveness of technology [38]. In recent years, multilateral development banks have adopted more restrictive finance policies for coal electricity generating plants to reduce emissions [4]. Exploring the impact of variations in financing costs on the feasibility of HELE plants in the Southeast Asia region would be another interesting research direction.

5. Conclusions

Across Southeast Asia, there is a vital need to deploy HELE technologies, rather than employing less-efficient subcritical technology. Deployment of HELE technologies is progressing in Southeast Asia, but the overall rate of deployment falls short of achieving the 2DS. ASEAN should therefore make increased efforts to eliminate generation from subcritical plants and increase generation from HELE plants to meet the 2Ds targets. In this study, it is revealed that the pollution control scenario (i.e., implementation of a carbon pricing policy) surpasses the other scenarios in displacing subcritical plants sooner to pave the way for HELE technologies.

The study also reveals that:

- The climate change mitigation and pollution control scenario (i.e., a mix of carbon price and emission control technologies) is the second-best driver scenario (at the cost of increased LCOE prices as compared to Scenario 2);
- Reduced coal prices and increased life spans benefit both HELE and subcritical coal-fired power plants;
- HELE coal-fired power plants are economically competitive against subcritical plants;
- A-USC coal-fired power plants are the most economically attractive choice for deployment in Southeast Asia, followed by USC and SC plants.

The conclusion is that HELE plants are economically competitive against the subcritical plants, and in the short run, the Southeast Asian economies should focus on devising and implementing carbon pricing to support quicker deployment of HELE and displacement of subcritical technologies. Ultimately, in the long-run, a strong carbon price signal will be needed with strict emission standards to enable HELE transition.

While this study focuses specifically on ASEAN countries, its broader lessons are applicable for global deployment of HELE coal plants.

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Abbreviations

ACE	ASEAN centre for energy
ASEAN	Association of southeast Asian nations
A-USC	Advanced ultra-supercritical
Btu	British thermal unit
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCT	Clean coal technology
CF	Capacity factor
CO_2	Carbon dioxide
deNOx	Denitrification

deSOx	Desulphurization
EPC	Engineering, procurement and construction
ERIA	Economic Research Institute for ASEAN and East Asia
ETP	Energy technology perspectives
FCR	Fixed charge rate
GAR	Gross as received
gce/kWh	Grams coal equivalent per kWh
GHG	Greenhouse gas
g/kWh	Grams per kilowatt hour
GW	Gigawatt
GWh	Gigawatt hours
HELE	High-efficiency low-emissions
Hg	Mercury
HHV	High heating value
IEA	International energy agency
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
IPCC	Intergovernmental panel on climate change
kcal/kg	Kilocalorie per kilogram
kg-CO_2/kg-coal	Kg of CO_2 per Kg of coal
kg-coal/kWh	Kg of coal per kilowatt hour
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelized cost of electricity
LHV	Low heating value
MMBtu	One million Btus
mt	Metric ton
MW	Megawatt
NOx	Nitrogen oxides
NO_2	Nitrogen dioxide
O&M	Operation and maintenance
$O\&M_{fixed}$	Fixed O&M charges
$O\&M_{variable}$	Variable O&M charges
OECD	Organization for economic co-operation and development
SC	Supercritical
SO_2	Sulphur dioxide
SOx	Sulphur oxides
ton/MWh	Ton per megawatt hour
TWh	Terawatt-hour
USC	Ultra-supercritical
US$	US dollars
2DS	2 °C scenario

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