Policies toward net-zero: Benchmarking the economic competitiveness of nuclear against wind and solar energy

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Abstract

Policymakers are increasingly discussing the role of nuclear and renewable energy in replacing fossil-fuelled power generation, especially coal. In this debate, a key discussion is about the economic competitiveness of nuclear energy, particularly compared to wind and solar. Remarkably, despite the growing interest, there is a lack of studies comparing the economics of nuclear power plants (traditional large reactors and small modular reactors) with wind and solar power plants in different decarbonisation scenarios. Through energy systems modelling analysis, this paper benchmarks the economics of nuclear with wind and solar energy for 11 decarbonisation scenarios simulating the effects of 5 energy policies in 5 Member States (i.e. Indonesia, Malaysia, Philippines, Thailand, and Vietnam) of the Association of South East Asian Nations (ASEAN). The findings highlight that nuclear energy is an economically competitive pathway towards net-zero if the overnight cost is comparable to recent nuclear power plants built in China and Korea. Contrariwise, if the overnight cost is comparable to recent nuclear power plants built in the UK, US, or France, a mix of wind and solar energy is more economically competitive. Furthermore, the findings provide a background for policy discussions and recommendations for ASEAN countries.

Keywords: small modular reactors; energy transition policy; net zero; scenario planning; ASEAN;

List of abbreviations

ASEAN	Association of South East Asian Nations
ACE	ASEAN Centre for Energy
AMS	ASEAN Member States
BAU	Business-As-Usual
EIA	Energy Information Administration
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IDC	Interest During Construction
IIASA	International Institute for Applied Systems Analysis
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Electricity
LR	Large Reactor
Mtoe	Million tonnes of oil equivalent
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NPV	Net Present Value
O&M	Operations and Maintenance
OECD	Organization for Economic Co-operation and Development
SMR	Small Modular Reactor
TDC	Total Discounted Cost
TEA	Techno-Economic Assessment
UK	United Kingdom
US	United States of America
WNA	World Nuclear Association

1 Introduction

As recently seen in the 26th Climate Change Conference, policymakers are increasingly discussing the role of nuclear and renewable energy in achieving the Sustainable Development Scenario [1]. Renewable and nuclear energy, along with changes in consumer behaviour, can enable the zero-emission target by 2100 set by the Intergovernmental Panel on Climate Change [2]. With the fast-rising energy demand, the dominance of fossil energy [3], and the urgency to address self-sufficiency [4] and net-zero target [5], several Asian countries are interested in nuclear and renewable energy (wind and solar in particular) [6, 7]. The pre-feasibility study by the ASEAN (Association of South East Asian Nations) Centre for Energy (ACE) suggests that Indonesia, Malaysia, Philippines, Thailand, and Vietnam are among the frontrunners in developing civilian nuclear power programmes in the region [8].

According to a study by the ASEAN Centre for Energy (ACE) [9], the ASEAN's primary energy demand reached 625 Million tonnes of oil equivalent (Mtoe) in 2017, and it is projected to grow at a rate of 4.1% per year reaching 1589 Mtoe in 2045. The electricity demand is projected to triple by 2040, increasing from 1002 TWh in 2017 to 3123 TWh by 2040, with coal remaining the largest source of electricity generation. In the Business-As-Usual (BAU) scenario, the increasing consumption of fossil fuels would lead to a growth in CO2 emissions from 1686 Million tonnes (Mt) in 2017 to 4171 Mt in 2040 [9]. The additional CO2 emissions from ASEAN between 2015 and 2040 are expected to be roughly equivalent to those of the world's fifth-highest emitter, Japan, in 2014 [10].

Coal is the principal source of the ASEAN's current and future primary energy supply. The ASEAN region's coal demand is expected to increase from 91 Mtoe in 2013 to 271 Mtoe by 2040, accounting for 25.5% of the total energy consumption [11]. While renewables (with a relevant role played by hydropower plants [12]) collectively meet around 15% of the region's energy demand [3], coal will remain, in the BAU, an important source of energy given the economic, geographical and geopolitical circumstances of ASEAN. However, the region is exploring alternative energy transition pathways [13] and multiple uses of different energy sources [14].

Nuclear energy is not new to the ASEAN region. Since the 1960s, several ASEAN Member States (AMS), such as Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, welcomed the development of a nuclear power programme [15]. The main argument for supporting the developments in nuclear energy lies with the cost of decarbonisation from a whole-system perspective [16] and the need to address energy security and climate considerations [17]. After nearly six decades of preparation, it is necessary to assess whether ASEAN policymakers should implement policies supporting the deployment of Nuclear Power Plants (NPPs) and, in particular, if policies should support the deployment of traditional LRs or Small Modular Reactors (SMRs), a combination of them, or should not support the deployment of NPPs. On this matter, a key debate is about the economic competitiveness of NPPs in general, and in particular with respect to renewable energy sources, especially wind and solar.

SMRs could be a suitable option in the context of ASEAN [18, 19]. However, what remains uncertain is the true economic benefits of adopting nuclear energy as a means toward net-zero in the context of ASEAN. A number of factors contribute to such uncertainty. First, there is a lack of clarity on the cost of nuclear energy in the context of Southeast Asia, especially when the economies of scale and the economies of multiples [20, 21] are taken into consideration. Next, there is uncertainty on the cost of decarbonisation at a system level when nuclear is considered as a replacement for coal and, more in general, fossil fuels. Third, there is a lack of understanding about how to design the most appropriate decarbonisation policy with nuclear energy in the technology portfolio. Last, there is uncertainty about the economic competitiveness of NPPs with respect to wind and solar power plants.

Through energy systems modelling analysis, this study aims to examine and compare the economics of nuclear with wind and solar energy in five AMS (i.e. Indonesia, Malaysia, Philippines, Thailand, and Vietnam). In particular, the objectives of this paper are:

1) To establish the cost and impact of using nuclear power (traditional LRs and SMRs) for decarbonisation;
2) To benchmark the competitiveness of NPPs with respect to a mix of wind and solar power plants in ASEAN countries;

3) To provide policy recommendations for net-zero pathways in ASEAN countries.

The first two objectives are addressed by a scenario-based analysis approach, which provides the background for policy recommendations. The key novelty of this paper lies in shedding light on the economic competitiveness of NPPs (LRs and SMRs) with respect to wind and solar in different decarbonisation scenarios, as well as in leveraging the quantitative economic analysis to derive policy recommendations for ASEAN countries.

The rest of the paper is structured as follows. Section 2 introduces SMRs and traditional LRs and provides an overview of the main energy systems modelling tools worldwide. Section 3 details the methodology adopted in this study. Section 4 presents and discusses the results, providing a series of policy messages. Section 5 discusses the policy implications of this study and concludes the paper by providing future research opportunities.

2 Background

2.1 The debate “Small Modular Reactors vs Large Reactors”

In Southeast Asia, as well as in other countries interested in nuclear energy, there is a growing debate about the dilemma of which nuclear power technology or reactor design is better to build [22]. Recently, this debate focused on the size of the reactors, particularly on the opportunity of adopting SMRs [23, 24]. SMRs are defined as “*newer generation [nuclear] reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises*” (Page 1) [25]. SMR designs are at different stages of development, as detailed in [26], and relate to all the main reactor categories: water-cooled reactors, high-temperature gas-cooled reactor, liquid-metal, sodium and gas-cooled reactors with fast neutron spectrum, and molten salt reactors [27].

As reviewed by Mignacca and Locatelli [21], a key discussion in the literature is about the economic competitiveness of SMRs with respect to traditional LRs. SMRs have been often considered uncompetitive with respect to LRs and other energy sources because of a misguided interpretation of the economy of scale principle (i.e. “bigger is better”) [20]. The economy of scale applies only “*ceteris paribus*", which is not the case for SMRs vs LRs. Indeed, SMRs present unique characteristics which need to be considered in the comparison. SMRs present three peculiar characteristics: size, modularisation and modularity. Figure 1 clarifies the difference between modularisation and +modularity and presents the meaning of monolithic stick-built plant (typical of traditional LRs) and pure standardisation.

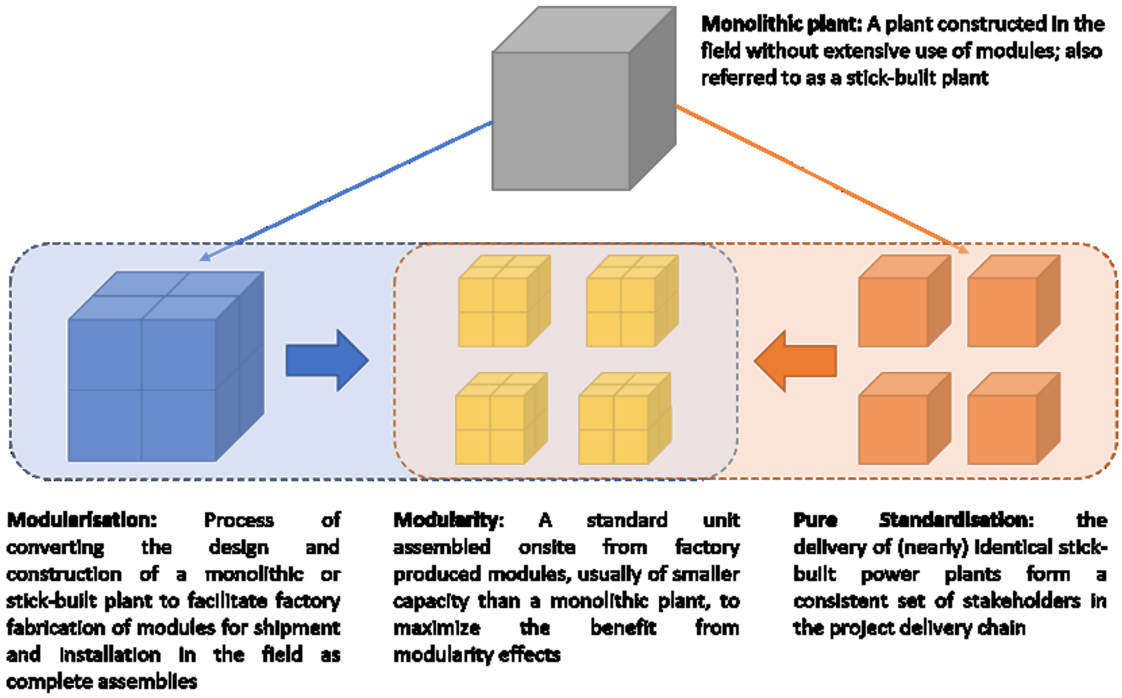


Figure 1: Stick-built construction - Modularisation - Standardisation – Modularity – Extracted from [21]

It is worth clarifying, as shown in Figure 1, that no one plant is completely stick-built, but each plant presents a degree of modularisation. Modularisation (and therefore factory fabrication) is expected to improve quality, reduce construction cost and schedule [28, 29]. Recent research also highlights how modularisation enables the implementation of circular economy initiatives in energy infrastructure [30, 31] and in the specific case of SMRs [32]. However, modularisation presents also challenges, such as module transportation activities [33], a higher project management effort [34], licensing and regulatory challenges [35].

Mignacca and Locatelli [21] present an overview of the main implications of modularity, such as the incremental capacity addition leading to a better cash flow profile [36], co-siting economies allowing to save indivisible costs (e.g. licences, human resources) [37], and better suitability for cogeneration with respect to LRs [38, 39]. The implications of modularisation and modularity are expected to compensate, at least partially, for the lack of economy of scale [40]. However, some research disagrees, denying some of the aforementioned implications of modularisation and modularity [41, 42], arguing, for instance, that an incredibly high number of SMRs is needed to overcome the lack of economy of scale.

Several energy systems modelling tools are available to compare scenarios presenting different energy sources including SMRs and LRs (and also wind and solar), as presented in the next section.

2.2 Energy systems modelling tools

There are several approaches to comparing the competitiveness of alternative power generation technologies. The economic analysis is usually the most preferred approach for most infrastructure projects. The main advantage of this approach is that it can help decision-makers better understand the implications of decisions by quantifying the consequences under various scenarios [43]. The analysis is often done by discounting future cash flows to current values, also known as the Net Present Value (NPV) [44].

Calculating the NPV by following a scientific and engineering framework is a necessary step toward gaining a better understanding of technological choices. As seen in several studies such as those by the OECD NEA and IEA [45] and EIA [46], the NPV approach is popularly used in energy modelling tools when evaluating the economic competitiveness of alternative power generation technologies based on indicators such as the Levelized Cost Of Electricity (LCOE). The LCOE provides an estimate of the average cost of generating electricity over the entire operating life of the power plants for a given technology, taking into account main cost components, such as capital costs, fuel costs, and operations and maintenance (O&M) costs.

The 2000s saw fast-evolving efforts in the development of energy systems modelling tools with some focus on the LCOE and Total Discounted Cost (TDC). Some of these modelling tools have been widely adopted by national agencies and international organisations for long-term planning. The ENPEP-BALANCE was developed by the Argonne National Laboratory [47] as a modelling tool to examine the economics of long-term electricity balance. LEAP is an integrated scenario-based energy-environment modelling tool that accounts for how energy is consumed, converted and produced in a given energy system under a range of alternative assumptions [48]. MESSAGE is developed by the International Institute for Applied Systems Analysis (IIASA) and designed for medium to long-term energy system planning, energy policy analysis, and scenario development [49]. MARKAL [50] and TIMES [51] are the least-cost driven modelling framework to evaluate the economics of alternative technology pathways toward net-zero.

Recent development in energy systems modelling tools also includes those built upon a generic Life Cycle Analysis (LCA) framework [52], which allows conducting change impact analysis [53] and the synchronisation of system lifetime when multiple systems interact with one another [54]. Such development allows expansion from traditional cradle-to-grave types of LCA towards energy systems modelling while ensuring consistency in system boundary definitions when accounting for environmental impacts due to system inputs [52].

Based on the generic LCA framework, Li, Nian [55] proposed the addition of a Techno-Economic Assessment (TEA) framework as an additional layer to the generic LCA framework, leading to an alternative energy systems modelling tool to profile future technology pathways. However, the LCA-TEA modelling framework was only applied to the demand side (air-conditioning) technology which is different from a conversion technology (such as power generation) in a typical energy modelling framework. As explained in the next section, adjustments and improvements to the LCA-TEA framework have been made in order to apply it to power generation.

3 Methodology

3.1 LCA-TEA framework

The main LCA-TEA methodology used in this study is developed upon the fundamental principles and concepts from several studies. The formulations are of authors' own deliberation. Following the generic LCA framework developed in [56], the life cycle carbon emissions of a given system can be expressed as

$$\begin{aligned} C_{sys} &= C_E + C_{NE} + C_{FUEL} \\ &= \sum_{n=1,2,\ldots} \left(p_n \times \left(\sum_{i=1,2,\ldots} c_{e,i} \times e_i + \sum_{i=1,2,\ldots} c_{ne,i} \times ne_i \right) \right) + C_{FUEL} \\ &= \sum_{n=1,2,\ldots} \left(p_n \times \sum_{i=1,2,\ldots} c_{e,i} \times e_i \right) + C_{FUEL} \end{aligned} \quad (1)$$

where C_{sys} represents the life cycle carbon emissions of the life cycle system; C_E represents carbon emissions due to energy input; C_{NE} represents carbon emissions due to non-energy input; C_{FUEL} represents carbon emissions due to the use of power plant fuel; p_n represents the "product" from each process of the life cycle system; e_i represents energy input per unit of p_n produced; ne_i represents the non-energy input per unit of p_n produced; $c_{e,i}$ represents the carbon emission factor of energy input; and $c_{ne,i}$ represents the carbon emission factor of non-energy input.

Similar to [55], adding the TEA layer partially follows the concepts described by the IEA's TIMES model [51]. The basic principle is that demand would always be satisfied by supply through a series of energy transformation processes, with each process representing one or more competing technologies. The demand is given as a time series, usually with a projected change over time. Several competing technologies represented as options can serve the same demand. In this study, a scenario-based simulation approach is adopted by manually specifying the technology or fuel mix for the power sector to observe the changes in total system cost, energy consumption and carbon emissions over the modelling period.

Similar to the demand side LCA-TEA framework, a simplified LCA-TEA framework on the supply side, as proposed in this study, can be conceptualised as shown in Figure 2. In this LCA-TEA framework, the focus of analysis is on the life cycle of power generation technologies. Each power plant option, as described in the LCA-TEA framework, represents a life cycle system of the corresponding power generation technology with its associated costs, efficiency, technical lifetime, and fuel use. The carbon emissions of each power plant technology are primarily determined by the carbon emission factor of fuel.

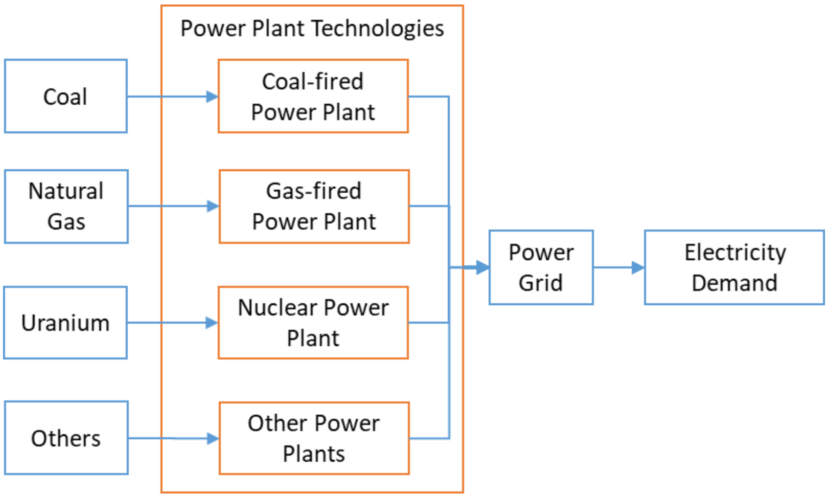


Figure 2 Conceptualised LCA-TEA analysis framework

Similar to the principle in TIMES, the TEA component follows a fundamental goal that demand must always be satisfied by supply which can be expressed as

$$ELC_{DM} = ELC_{PP} \quad (2)$$

where ELC_{DM} represents the electricity demand calculated at the grid- or system-level, and ELC_{PP} represents the electricity production from all active power plants.

The needed power plant capacity (CAP_t) at year t can be computed based on the end-use energy demand expressed as

$$CAP_t = ELC_t/(8760 \times AF_t \times CF_t) \quad (3)$$

where AF_t represents the annual availability factor of the power plant technology; CF_t represents the capacity factor of the power plant if applicable. The use of 8760 is under the assumption that the electricity demand and supply are both expressed in terms of kWh. In this study, both AF_t and CF_t are assumed to be the regional average of all plants of the same technology.

The introduction of AF_t and CF_t is mainly due to the operating characteristics of power plants. Most power plants require certain downtime due to scheduled maintenance, bidding strategies, and unexpected incidents. There is effectively an "oversizing" of the plant to make sure that the total amount of electricity produced by the power plant fleet will always meet the electricity demand on an aggregated basis. As such, these variables are usually not required or applicable to demand-side technologies, such as air-conditioning systems or cars.

The annual investment cost in the needed capacity, in general, can be expressed as

$$INV_t = CAP_{add,t} \times INV\_CAP_t \tag{4}$$

$$CAP_{add,t} = (CAP_t - CAP_{t-1}) + CAP_{retired,t-1} \tag{5}$$

where INV_CAP_t represents the investment cost per unit of power plant capacity; $CAP_{add,t}$ represents the added capacity in the current period (t) as compared to the immediate past period ($t-1$); and $CAP_{retired,t-1}$ represents the amount of new capacity that has been invested or added to the system earlier but has reached end-of-life in the immediately preceding period $t-1$.

CAP_t can change over time due to the change in energy demand, capacity retirement (due to technology or process end-of-life), and other factors such as forced retirement due to policy goals. Depending on those factors, there could be a need to increase the capacity of the technology due to an increase in demand. Depending on the change in process capacity between the current period and the previous period as expressed by $CAP_t - CAP_{t-1}$ as well as $CAP_{retired,t-1}$, the need to invest in new capacity would be determined based on the computed value of $CAP_{add,t}$ and the following logic

$$\begin{aligned} &If\ CAP_{add,t} > 0, INV_t = CAP_{add,t} \times INV\_CAP_t \\ &If\ CAP_{add,t} \leq 0, INV_t = 0 \end{aligned} \tag{6}$$

Under the LCA-TEA framework [55], it is sufficient to focus on the operational stage carbon emissions for each process of the process chain in a pathway-level assessment. As such, the total carbon emissions due to power generation at time t can be expressed as

$$C_{sys,t} = C_{FUEL,t} \tag{7}$$

where $C_{FUEL,t}$ represents the summation of all carbon emissions due to the use of different types of power plant fuel by different corresponding power plant technology at time t.

3.2 Economics of power generation

Two indicators are proposed to estimate the economic merit of alternative system configurations, namely, the Total Discounted Cost (TDC) and the Levelised Cost of Electricity (LCOE).

The TDC provides an estimate of the cost of electricity production over the entire operating life of a given power generation technology, taking into account main cost components such as capital costs, fuel costs, and O&M costs. It is a flexible analytical model that allows specific cost factors such as contingency, reserve and energy security factor to be considered. By definition, the TDC can be expressed as

$$TDC = \sum_t (INV_t + O\&M_t + FUEL_t + DECOM_t) \times (1+r)^{-t} \tag{8}$$

where INV_t represents the investment costs, i.e. the sum of the "overnight cost" and the Interest During Construction (IDC). The overnight cost can be defined as "*the base construction cost plus applicable owner's cost, contingency, and first core costs. It is referred to as an overnight cost in the sense that time value costs (IDC) are not included*" [57] (Page 25);

$O\&M_t$ represents O&M costs, i.e. "*all non-fuel costs, such as costs of plant staffing, consumable operating materials (worn parts) and equipment, repair and interim replacements, purchased services, and nuclear insurance. They also include taxes and fees, decommissioning allowances, and miscellaneous costs*" [57] (Page 33);

$FUEL_t$ represents fuel costs, i.e. the costs related to the nuclear fuel cycle, from the mining of the uranium ore to the final high-level waste disposal [58];

$DECOM_t$ represents the decommissioning costs, i.e. "*all activities, starting from planning for decommissioning, the transition phase (from shutdown to decommissioning), performing the decontamination and dismantling and management of the resulting waste, up to the final remediation of the site*" [59](Page 6);
r represents the discount rate, i.e. the interest rate used to determine the present value of future cash flows [60].

The main results, the levelised unit cost of energy generation or the LCOE, can provide insights into the main cost factors of energy production systems [39].

The LCOE can be expressed as

$$LCOE = \frac{TDC}{\sum_t ELC_t \times (1+r)^{-t}} \tag{9}$$

where ELC_t represents electricity production in year *t*.

The discount rate is assumed to be 5%; the assumption of a constant discount rate when computing the discounted costs is also consistent with earlier studies such as [44] and [38].

3.3 Data and assumptions

The starting point of each policy simulation is the Business-As-Usual (BAU) scenario of the considered ASEAN countries (Indonesia, Malaysia, Philippines, Thailand, and Vietnam), as detailed in the appendix. The BAU "*assumes that government policies, technologies and social preferences continue to evolve in a manner and speed seen over the recent past*" [61]. The BAU inputs are provided by [62], which reports the electricity demand projection from 2020 to 2040 and the related technology generation mix (%) for each of the aforementioned countries. In the analysis, we extended the [62] trend of the electricity demand by assuming the same annual demand increase from 2035 to 2040 in the timeframe 2040-2050. We also assumed the same generation mix (%) of 2040 in the timeframe 2040-2050 to simulate longer-term scenarios, as shown in the appendix.

Table 1 reports the costs and performance of the energy technologies. The key issue regarding the cost of nuclear power plants (LRs or SMRs) is that no commercial plant has been built yet in the area; therefore, assumptions need to be made. As further elaborated in the next section, two values for the LR overnight cost have been considered. An "optimistic" value of \$2328/kW, calculated as the average overnight cost of the new build NPPs in China and Korea [63], and a "conservative" value of \$8540/kW, calculated as the average overnight cost of the new build NPPs in UK, US, and France [63-65]. The SMR overnight cost has been considered 9% higher than traditional LRs, calculated as the average of the estimations provided by [66, 67] (REF).

O&M costs have been considered 19% higher than LRs, as reported by [68]. Where IRENA [69] reports a range of values (e.g. 70-80% is the capacity factor for coal), we adopted the average. ERIA [62] reports "others" in the technology generation mix of the considered ASEAN countries; we assumed "other" as a mix of wind and solar, and calculated the related values (e.g. overnight cost, O&M costs) as the average of wind and solar technologies.

Table 1: Energy technologies cost and performance – Data from [63-67, 69] – Lifecycle GHG Emission Intensity from (Houses of Parliament, 2011; WNA, 2011)

Technology	Overnight cost (\$/kW)	O&M costs (\$/kW)	Lifetime (Years)	Capacity factors (%)	Lifecycle GHG Emission Intensity (tonnes CO2e/GWh)
Coal	1300	52	60	75	888
Oil	1200	18	50	25	733
Natural gas	1000	40	30	55	499
LR	2328 (optimistic) – 8540 (conservative)	138	60	82.5	29
SMR	2538 (optimistic) – 9309 (conservative)	165	60	82.5	29
Hydro	2500	50	40	50	26
Geothermal	2500	100	50	70	34
Wind and solar	1350	37.5	30	23	55

3.4 Scenario and policy designs

With respect to the BAU scenario, we developed five alternative policies clustered in 2 main groups: Nuclear-based decarbonisation (Policies 1-2-3), Wind and solar-based decarbonisation (Policies 4-5).

Regarding nuclear-based decarbonisation, we developed three alternative policies based on the introduction of different levels of nuclear power in the electricity generation mix from 2040 to 2050 (Policy 1, Policy 2, and Policy 3 in Table 2). These three policies have been simulated twice: 1) Considering the "optimistic" value for LR and SMR overnight cost, and 2) Considering the "conservative" value for LR and SMR overnight cost. These values are reported in Table 1.

Policy 1 is based on the introduction of modern LRs in the electricity generation mix. Modern LRs are standard technologies, commercially viable, including several designs currently under construction in several countries, even nuclear newcomers such as Turkey and the United Arab Emirates (IAEA, 2021). Therefore, the considered ASEAN countries have the option to build LRs engaging with established nuclear vendors (WNA, 2021). The transition from coal to LRs could be at different levels. We assumed three levels (i.e. 10%, 50%, and 100%), corresponding to scenarios A, B, and C in Table 2.

The considered ASEAN countries aimed at phasing out coal also have the option to add SMRs to their portfolio later to exploit their advantages (e.g. cogeneration). This policy option is captured in Policy 2. This analysis considered SMRs based on proven technologies (e.g. pressurised water reactors). Policy 2 can also see different levels of coal phase-out; therefore, we modelled different scenarios, as in Table 2. We also considered the option of a policy focused on complete decarbonisation by 2050. This extreme policy requires a large number of NPPs, which could reasonably be a mix of LRs and SMRs, as described in Policy 3 in **Errore. L'origine riferimento non è stata trovata.**.

Regarding wind and solar-based decarbonisation, we developed two alternative policies based on the introduction of different levels of wind and solar in the electricity generation mix from 2025 to 2050 (Policy 4 and Policy 5 in Table 2). Policy 4 captures the transition from coal to wind and solar. As in the case of nuclear, the transition could be at different levels. We assumed, also in this case, three levels (i.e. 10%, 50%, and 100%), corresponding to scenarios H, I, and J in Table 2. Policy 5 is a more extreme policy leading to complete decarbonisation driven by wind and solar, gradually replacing the entire fossil fuels from 2025 to 2050.

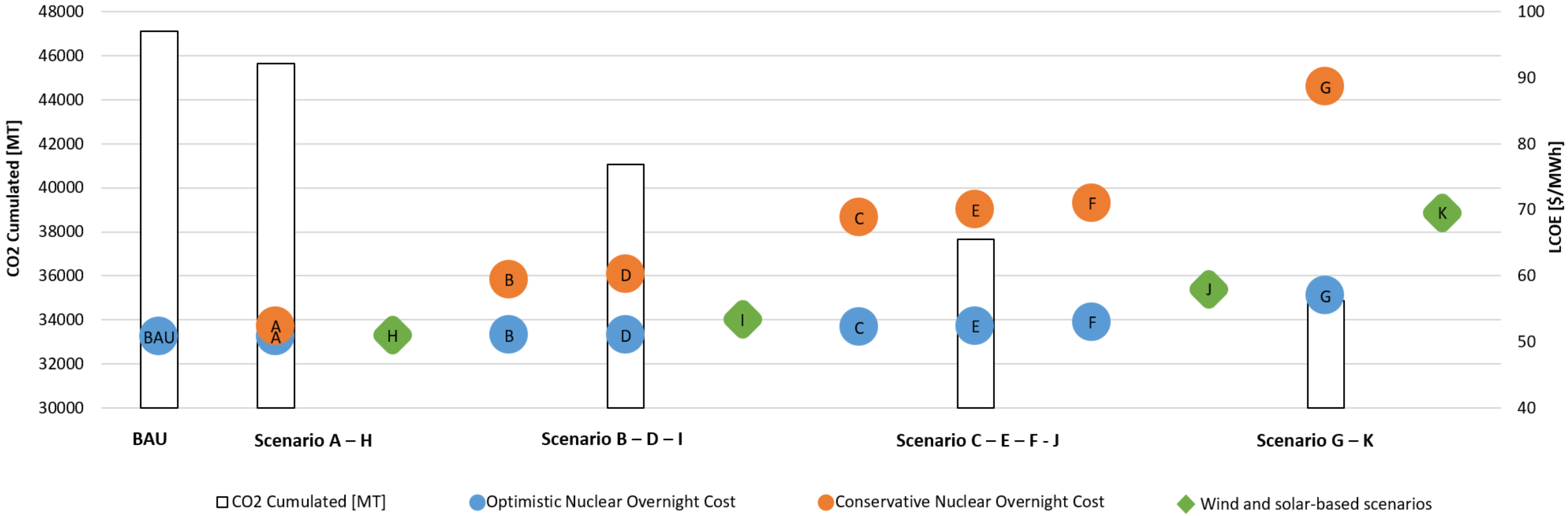
Table 2: Scenario and policy definition

Scenario definition	Nuclear-based decarbonisation			Wind and solar-based decarbonisation	
	Policy 1 Coal to LRs	**Policy 2** Coal to SMRs	**Policy 3** Complete decarbonisation	**Policy 4** Coal to Wind & Solar	**Policy 5** Complete decarbonisation
Scenario A 10% coal to LRs	X				
Scenario B 50% coal to LRs	X				
Scenario C 100% coal to LRs	X				
Scenario D 50% coal to LRs (50%) and SMRs (50%)		X			
Scenario E 100% coal to LRs (50%) and SMRs (50%)		X			
Scenario F 100% coal to SMRs		X			
Scenario G 100% fossil fuels to LRs (50%) and SMRs (50%)			X		
Scenario H 10% coal to Wind (50%) and Solar (50%)				X	
Scenario I 50% coal to Wind (50%) and Solar (50%)				X	
Scenario J 100% coal to Wind (50%) and Solar (50%)				X	
Scenario N 100% fossil fuels to Wind (50%) and Solar (50%)					X

4 Results and discussion of alternative energy policies

4.1 Levelised cost of electricity and total carbon emissions

This section presents and discusses the LCOE and cumulated CO2 emissions resulting from the scenario simulations for the five alternative policies described in section 3.4. As aforementioned, Policy 1-3 have been simulated twice, i.e. once for optimistic and once for conservative nuclear overnight cost. Considering that the findings have the same trend among the five AMS in terms of how the LCOE and cumulated CO2 change in response to Policy 1-5, the average LCOE and cumulated CO2 values of the five AMS have been calculated and reported in Figure 3. In addition, the penetration of wind and solar and the penetration of nuclear in the generation mix determine, other things being equal, almost the same cumulated CO2. Therefore, a unique value (the higher) of cumulated CO2 is reported in Figure 3 for the same percentage of penetration (e.g. 10% nuclear and 10% Solar and Wind). Table A2-6 in the appendix details the findings for each country separately. The different percentage variation in LCOE and CO2 among countries is due to a different technology mix in the BAU.



BAU
Business-As-Usual
Scenario A
10% coal to LRs (Optimistic/Conservative)
Scenario B
50% coal to LRs (Optimistic/Conservative)
Scenario C
100% coal to LRs (Optimistic/Conservative)

Scenario D
50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)
Scenario E
100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)
Scenario F
100% coal to SMRs (Optimistic/Conservative)
Scenario G
100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)

Scenario H
10% coal to Wind (50%) and Solar (50%)
Scenario I
50% coal to Wind (50%) and Solar (50%)
Scenario J
100% coal to Wind (50%) and Solar (50%)
Scenario K
100% fossil fuels to Wind (50%) and Solar (50%)

Figure 3: Overall comparison of the findings

The following policy messages can be derived from Figure 3.

- If a country decides to replace 10% of coal with LRs (Scenario A) or with a mix of Wind and Solar power plants (Scenario H), the reduction of cumulated CO2 emissions in the timeframe 2020-2050 would be negligible in both cases (3%).
- The replacement of 50% coal with NPPs (Scenario B and D) or with a mix of Wind and Solar power plants (Scenario I) would lead to a relatively low (≈13%) reduction of cumulated CO2 in the timeframe 2020-2050. This is also true in the case of 100% coal replacement (≈20%) (Scenario C, E, F, and J) and complete decarbonisation (≈26%) (Scenario G and K). This is due to the late introduction of NPPs, starting in 2040 with gradual addition until 2050, and also the late introduction of Wind and Solar power plants, starting in 2025 but with very low addition (≈1-4%) until 2040. The assumption of a very low addition in the first years is made in order to ensure a fair comparison of nuclear with wind and solar in terms of CO2 reduction and impact on LCOE and TDC and, at the same time, simulate realistic scenarios. Therefore, even if an ASEAN country decided today to replace 100% of fossil fuels with NPPs or a mix of Wind and Solar power plants, the cumulated CO2 in the timeframe 2020-2050 would be slightly lower than the BAU. However, it is worth stressing that Figure 3 shows the cumulated CO2 in 2020-2050. Figure 4 in the next section shows the CO2 reduction in the specific year 2050.
- In terms of LCOE, Figure 3 shows the relevant findings:

  1) The replacement of coal with NPPs (Policy 1 and 2) represents the most economically competitive pathway to attain deep decarbonisation only if the nuclear overnight cost is comparable to recent NPPs built in China and Korea. Conversely, if the nuclear overnight cost is comparable to recent NPPs built in the UK, US, or France, a mix of Wind and Solar power plants is the most economically competitive pathway to attain deep decarbonisation (Policy 7). The same is valid in the case of complete decarbonisation (Policy 3 and Policy 8).

  2) All the policies (1-5) determine an increase in the LCOE. This is a consequence of the higher economic competitiveness of coal with respect to both NPPs and wind and solar power plants. The increase is negligible in the case of 10% coal replacement (<1% in the case of wind and solar and optimistic nuclear overnight cost, ≈3% higher in the case of conservative nuclear overnight cost) but substantial in the case of complete

decarbonisation (≈12% higher in the case of optimistic nuclear overnight cost, ≈37% higher in the case of Wind and Solar, and 74% higher in the case of conservative nuclear overnight cost).

4.2 Policy effect on CO2 by 2050

Figure shows the CO2 in the specific year 2050 in the scenarios presented in Table 2 for the five AMS.

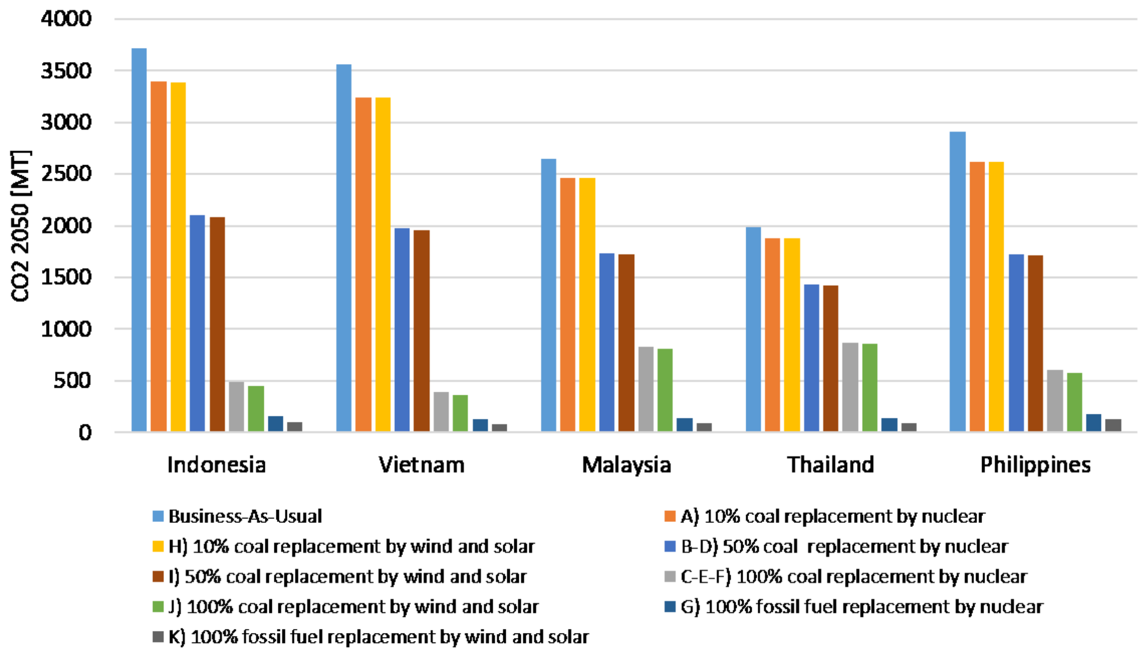


Figure 4: CO2 variation in 2050 from the BAU to the Scenarios (A-K)

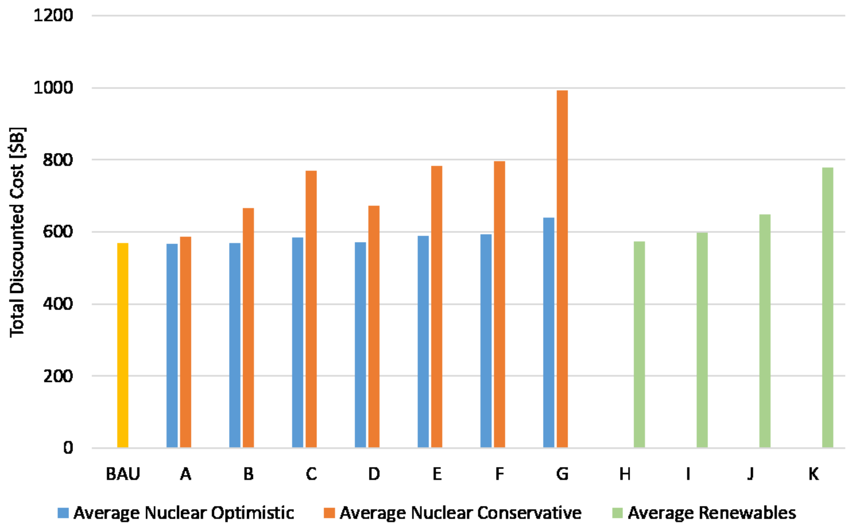
Three policy messages can be derived from Figure :

- If a country decided to replace 10% of coal with NPPs (Scenario A) or with a mix of Wind and Solar (Scenario H), the CO2 decrease in 2050 with respect to the BAU would be relatively low (≈5-11%).
- In the case of 50% coal replacement (Scenarios I, B, and D), the CO2 would considerably (≈37-49%) decrease in 2050 with respect to the BAU. The decrease is less considerable (≈30%) for Thailand due to the different percentage of coal in the generation mix.
- The impact of complete decarbonisation (Scenario G and K) on the CO2 in 2050 with respect to the impact of 100% coal replacement (Scenario C-E-F-J) would be relatively low.

This is due to the high percentage of coal in the generation mix with respect to other fossil fuels (i.e. natural gas and oil).

4.3 Total Discounted Cost

Figure shows how the TDC changes in the proposed scenarios with respect to the BAU. For the sake of clarity, the TDC considers the different lifetime between nuclear and renewables. As in Figure 3, the average of the TDC values of the five AMS is reported in Figure 5. Table A2-6 in the appendix detail the findings. The substantial difference in the TDC for the five AMS shown in the appendix is due to the different magnitude of the investment needed.



BAU
Business-As-Usual
Scenario A
10% coal to LRs (Optimistic/Conservative)
Scenario B
50% coal to LRs (Optimistic/Conservative)
Scenario C
100% coal to LRs (Optimistic/Conservative)
Scenario D
50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)
Scenario E
100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)
Scenario F
100% coal to SMRs (Optimistic/Conservative)
Scenario G
100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)
Scenario H
10% coal to Wind (50%) and Solar (50%)
Scenario I
50% coal to Wind (50%) and Solar (50%)
Scenario J
100% coal to Wind (50%) and Solar (50%)
Scenario K
100% fossil fuels to Wind (50%) and Solar (50%)

Figure 5: Total Discounted Cost of the scenarios with respect to the BAU

Three policy messages can be derived from Figure :

- All the policies would determine an increase in the LCOE with respect to the BAU. Regarding Policy 1 (Scenario A, B, and C) and Policy 2 (Scenario, D, E, and F), the size of the increase depends on the NPP overnight cost. In the case of optimistic nuclear overnight cost, the variation would be negligible, conversely substantial in the case of conservative overnight cost. Policy 4 (H, I, and J) would determine an increase or a decrease in TDC with respect to Policy 1 and 2 according to the nuclear overnight cost (optimistic vs conservative).

- Policy 2 (Scenario D, E, and F) would lead to an increase in the TDC with respect to Policy 1 (Scenario A, B, and C), due to the higher SMR overnight cost.
- Regarding the complete decarbonisation, the increase in TDC determined by Policy 5 (Scenario K) is between Policy 3 (Scenario G) with conservative nuclear overnight cost and Policy 3 with optimistic nuclear overnight cost.

5 Moving forward

5.1 Conclusions

Eleven scenarios have been designed to simulate the effects of five energy policies leading to the replacement of fossil energy with nuclear power technologies (both LRs and SMRs) or with wind and solar technologies. For each policy, the TDC, LCOE and CO2 emissions are computed based on the entire modelling period for identifying the most plausible pathways for five AMS (i.e. Indonesia, Malaysia, Philippines, Thailand, and Vietnam) to adopt nuclear and/or wind and solar energy.

As expected, replacing fossil fuels with nuclear or wind and solar energy will increase the cost of electricity but with the benefits of decarbonisation towards net-zero target [5, 70]. A key result is that nuclear energy (SMRs, LRs, or a combination of them) can be the most economically competitive pathway to attain deep decarbonisation only if the overnight cost is comparable to recent NPPs built in China and Korea. Conversely, if the overnight cost is comparable to recent NPPs built in the UK, US, or France, a mix of wind and solar energy is the most economically competitive pathway to attain deep decarbonisation.

The published information available on the economics of nuclear energy in Southeast Asia is very limited, particularly in the scientific literature. The cost of SMRs, as assumed in this study, is higher than those advised by present nuclear energy companies, such as Seaborg Technologies, Core Power and ThorCon Energy, which are actively engaging the Southeast Asian market. Due to very limited literature available on the economics of nuclear energy in Southeast Asia, it is challenging to verify the claimed cost by the aforementioned nuclear vendors. However, based on the results of this study, it is reasonable to assume that nuclear energy could represent an economically plausible option, with the Philippines [71], Indonesia [72], and Singapore [73], which announced their respective plans to develop capabilities that are the preconditions for developing a nuclear energy programme.

The limitations of this research can be categorised into two main domains: 1) General methodological limitations and 2) Specific limitations of this study. Regarding the general methodological limitations, we mention the “usual” limitation of economic analyses. Our model relies on the concept of the time value of money: the choice of the discount rate substantially influences the analysis [74].

Regarding the specific limitations of this study, first, we did not include the financial constraints of investors considering unlimited access to financing (particularly relevant for nuclear, as also stressed in Section 5.2) and unlimited supply chain (including both materials and people). In terms of people and organisations, this study did not consider the capabilities (further discussed in Section 5.2) needed to implement the simulated energy policies and the costs to develop such capabilities. Last, grid-level costs (e.g. grid extension, grid reinforcement) have not been modelled.

5.2 Policy recommendations for net-zero pathways

Based on the results of this study, the following policy recommendations are presented:

- Developing policies supporting the deployment of NPPs at regional level

The findings show how nuclear is economically competitive only if the overnight cost is in the order of magnitude of recent NPPs in China and South Korea. In order to reach a comparable value of overnight cost, a series of initiatives need to be developed, such as the deployment of NPPs at regional level, which would decrease the cost by harnessing the economy of multiples since LRs and/or SMRs will be built across the region. Therefore, the ideal solution for the AMS is to cooperate and collaborate on developing similar nuclear policies leading to a single (or two) standard reactor design built across the region.

- Regulatory harmonization

Considering the potential advantages of standardisation, an important path forward for ASEAN is to establish consistent policy and regulatory requirements. In the specific case of NPPs, as stressed by [35], the harmonization of law and licensing process is a key enabling factor for the standardisation of NPPs, which leads to the economy of multiples. However, ASEAN needs to agree on at least the minimum common legislation and licensing process for NPPs enabling all nuclear power plants to be connected to the regional power grid through an agreed market mechanism.

- Invest in domestic capabilities

The need to build a series of NPPs or wind and solar power plants or a combination of them generates the opportunity for ASEAN to become an association of world-leading nuclear and/or renewable countries in the long term. At the moment, there is a lack of experience in building and operating commercial NPPs; however, several ASEAN Member States, such as Indonesia, Malaysia, Philippines, Vietnam, and Thailand, are considered the frontrunners capable of making the next move as newcomer countries in nuclear energy [8]. Therefore, it is critical for ASEAN to invest in the domestic nuclear competence and supply chain so as to prepare for the adoption of nuclear energy in the long term. This requires the involvement of a network of organisations, such as manufacturers, regulators, service providers and universities [75] and would lead to the creation of know-how, scientific development and an improved import-export balance [21]. In the specific case of nuclear, in the short-medium term, ASEAN countries are expected to be turnkey importers; however, in the long term, as in the case of Korea [76], there are opportunities for becoming global exporters.

- Short-term action and long-term view

In the time frame from 2020-2050, the amount of CO2 emissions that can be avoided by deploying NPPs is limited because of the long planning and construction time. Therefore, by deploying NPPs instead of wind and solar, which can be constructed faster, an opportunity of saving CO2 emissions is lost. Therefore, wind and solar power plants can be built in the short term while, in the middle term, NPPs can be included in the grid. This might be ideal since NPPs can provide dispatchable power as fossil-fuel technologies are being phased out (coal and gas). On the nuclear front, the emergence of SMR technologies and reputable start-up nuclear companies means ASEAN could choose from a portfolio of nuclear power technologies that are most appropriate for meeting respective national energy and climate goals. As such, it is necessary for ASEAN to identify areas of use case (e.g. hydrogen production, chemical manufacturing, power generation) and adopt a vendor-neutral approach [77]. Given the multiple benefits of SMRs in a "post-Fukushima setting" [17], SMRs could represent a plausible option for ASEAN to scale up as a regional market for nuclear power technologies.

- Developing policies supporting circular economy initiatives

Circular economy initiatives determine the major benefits if considered in the early design stage [31, 78] or, more in general, "the earlier the better". Considering the high number of identical or nearly identical power plants that should be built for each of the alternative policies considered, there is a relevant opportunity to implement circular economy initiatives in the AMS (e.g. reuse modules and components across power plants built in different time horizons). Moreover, in the specific case of NPPs, since ASEAN is starting with a blank sheet of paper, circular economy initiatives can be practised from the very first NPP.

- Defining the financing structure

The financing represents a critical issue for capital intensive infrastructures, which are well-known for being often delivered over budget and late [79], leading to a lack of confidence by investors [80]. In terms of financing, SMRs are often considered advantageous with respect to traditional LRs due to the cost of a single SMR being substantially less than a single LR and the opportunity of generating revenues from the first unit/s while the other/s are still under construction [21]. However, the fact that no one truly modular SMR has been built yet represents a relevant obstacle for SMR financing with respect to the greater experience in building LRs. In general, ASEAN countries should define the financing structures for both LRs, SMRs, wind and solar power plants, or a combination of them.

5.3 Future research opportunties

This is the first study benchmarking nuclear (LRs, SMRs, and a combination of them) and wind and solar in the ASEAN context. This study can pave the way for several research opportunities, as now briefly described:

- Expanding the analysis to an interconnected ASEAN Power Grid

The ASEAN Power Grid, as a regional effort toward energy market integration, can create additional opportunities for nuclear and wind and solar energy deployment. With an interconnected ASEAN Power Grid, the overall demand for clean electricity can be further expanded, which creates opportunities for further replication of identical or nearly identical power plants. Especially in the context of SMRs, increasing the deployment of the same design will lead to reductions in the capital cost and hence the cost of electricity, ultimately enabling countries otherwise hardly embracing nuclear energy to also benefit from the nuclear energy deployment in AMS. A possible research aim should be to investigate to what extent an interconnected power grid might change the results of our analysis.

- Examining the potential monopoly countereffect

As aforementioned, standardisation is often one of the main factors to reduce the cost of power plants, especially capital-intensive such as NPPs. A possible countereffect of the standardisation is the monopoly. Overly relying on a particular design or vendor would gradually reduce the negotiating power, therefore, exposing additional unnecessary risks to the region in commissioning future projects. The potential monopoly countereffect should be examined. Possible research should investigate what kind of governance and market structure (Monopoly, Oligopoly etc.) might foster the decarbonisation in ASEAN countries.

- Investigating other implications of deep decarbonisation

Setting a target for clean energy, such as nuclear energy deployment, is likely to lead to disruptions to the current power sector planning in ASEAN. Depending on the retirement profile of currently operating assets, an ambitious clean energy replacement target is likely to lead to stranded assets caused by the early retirement of operable assets. Disruptions to the power sector planning can have repercussions on the upstream fossil fuel mining industry and the supply chain in general. If not managed properly, such disruptions can bring negative impacts to economic growth and social stability, which could both translate to costs not accounted for in this study. The aim of this research would be to establish the wider consequence of deep decarbonisation and, therefore, how energy policies impact the economy and wellbeing of citizens of ASEAN countries.

- Conducting a financial analysis

This study deals with the economics and decarbonisation potential of five energy policies in the ASEAN context, focusing on the cost implications of 11 scenarios. The other side of the coin, i.e. the financial aspect of such policies, is neglected. Therefore, possible future research should investigate financial aspects, such as, for instance, defining the financing model supporting the deployment of NPPs and wind and solar power plants in the five policies simulated and discussed in this paper. The financial analyses might test different levels of the discount rate, taxes, and/or other financial parameters.

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Appendix

Table A1: Power sector fuel mix projections for selected ASEAN Member States in the business-as-usual scenario [62]

Indonesia	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	74.1	73.6	78.3	74.1	70.3	70.3	70.3
Oil	3.7	3.3	2.2	1.9	1.6	1.6	1.6
Natural gas	17.9	16.8	14.8	17.8	22.7	22.7	22.7
Hydro	2.6	4.2	3.1	3.2	2.7	2.7	2.7
Geothermal	1.5	1.9	1.4	2.3	2	2	2
Others	0.2	0.2	0.2	0.6	0.7	0.7	0.7
Malaysia	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	42.2	39.2	38.5	38.5	39.6	39.6	39.6
Oil	1	0.7	0.6	0.5	0.4	0.4	0.4
Natural gas	44.5	47.1	50	51.8	52	52	52
Hydro	9.3	10.5	8.9	7.5	6.5	6.5	6.5
Geothermal	0	0	0	0	0	0	0
Others	3	2.5	2.1	1.7	1.5	1.5	1.5
Vietnam	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	64	62	63.5	66.6	68.9	68.9	68.9
Oil	0	0	0	0	0	0	0
Natural gas	15.5	20.1	21.3	20.6	20.1	20.1	20.1
Hydro	20.4	17.8	15.1	12.7	11	11	11
Geothermal	0	0	0	0	0	0	0
Others	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Philippines	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	45.4	48.3	49.6	50.2	48.7	48.7	48.7
Oil	5.1	4.60	3.9	3.4	3.4	3.4	3.4
Natural gas	18.4	17.9	20.4	22.4	25.9	25.9	25.9
Hydro	11.7	11.7	10.1	9.1	8.2	8.2	8.2
Geothermal	14	12.7	11.6	10.8	9.90	9.90	9.90
Others	5.40	4.8	4.3	4.1	3.8	3.8	3.8
Thailand	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	16.5	16	16.1	19.5	24.4	24.4	24.4
Oil	0.1	0.3	0.3	0.7	1	1	1
Natural gas	69.4	65.4	63.5	58	54.6	54.6	54.6
Hydro	5.3	5.4	5.6	5.7	5	5	5
Geothermal	0	0	0	0	0	0	0
Others	8.7	12.9	14.6	16.1	15	15	15

Table A2: Indonesia – Summary of the findings

Scenario	LCOE [$/MWh]	Total Discounted Cost [$B]	CO2 Cumulated [MT]	CO2 in 2050 [MT]
Business-As-Usual	63	702	60803	3716
Scenario A 10% coal to LRs (Optimistic/Conservative)	63 - 65	701 - 729	58967	3393
Scenario B 50% coal to LRs (Optimistic/Conservative)	63 - 75	704 - 839	52572	2102
Scenario C 100% coal to LRs (Optimistic/Conservative)	65 - 88	725 - 985	47844	488
Scenario D 50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	63 - 76	710 - 850	52572	2102
Scenario E 100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	65 - 90	732 - 1003	47844	488
Scenario F 100% coal to SMRs (Optimistic/Conservative)	66 - 91	738 - 1021	47844	488
Scenario G 100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	68 - 101	761 - 1133	45433	156
Scenario H 10% coal to Wind (50%) and Solar (50%)	63	707	58705	3390
Scenario I 50% coal to Wind (50%) and Solar (50%)	66	741	51913	2084
Scenario J 100% coal to Wind (50%) and Solar (50%)	73	812	47117	451
Scenario K 100% fossil fuels to Wind (50%) and Solar (50%)	82	915	44624	97

Table A3: Malaysia – Summary of the findings

Scenario	LCOE [$/MWh]	Total Discounted Cost [$B]	CO2 Cumulated [MT]	CO2 in 2050 [MT]
Business-As-Usual	43	480	42156	2644
Scenario A	43– 44	478 - 494	41131	2463

10% coal to LRs (Optimistic/Conservative)				
Scenario B 50% coal to LRs (Optimistic/Conservative)	43 - 50	481 - 556	37533	1735
Scenario C 100% coal to LRs (Optimistic/Conservative)	44 - 57	491 - 637	34870	826
Scenario D 50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	43 - 50	482 - 562	37533	1735
Scenario E 100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	44 - 58	495 - 648	34870	826
Scenario F 100% coal to SMRs (Optimistic/Conservative)	45 - 59	499 - 658	34870	826
Scenario G 100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	51 – 84	571 - 936	31358	134
Scenario H 10% coal to Wind (50%) and Solar (50%)	43	483	40995	2461
Scenario I 50% coal to Wind (50%) and Solar (50%)	45	502	37190	1725
Scenario J 100% coal to Wind (50%) and Solar (50%)	48	542	34463	805
Scenario K 100% fossil fuels to Wind (50%) and Solar (50%)	65	723	30761	86

Table A4: Vietnam – Summary of the findings

Scenarios	LCOE [$/MWh]	Total Discounted Cost [$B]	CO2 Cumulated [MT]	CO2 in 2050 [MT]
Business-As-Usual	57	641	55840	3557
Scenario A 10% coal to LRs (Optimistic/Conservative)	57 - 60	641 - 668	54040	3241
Scenario B 50% coal to LRs (Optimistic/Conservative)	57 - 69	644 - 776	47781	1975
Scenario C	59 - 82	664 - 919	43148	393

100% coal to LRs (Optimistic/Conservative)				
Scenario D 50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	58 - 70	649 - 787	47781	1975
Scenario E 100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	60 - 84	671 - 936	43148	393
Scenario F 100% coal to SMRs (Optimistic/Conservative)	60 - 85	677 - 954	43148	393
Scenario G 100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	62 - 93	698 - 1045	41090	130
Scenario H 10% coal to Wind (50%) and Solar (50%)	58	646	53813	3237
Scenario I 50% coal to Wind (50%) and Solar (50%)	61	680	47199	1957
Scenario J 100% coal to Wind (50%) and Solar (50%)	67	750	42513	357
Scenario K 100% fossil fuels to Wind (50%) and Solar (50%)	75	843	40370	84

Table A5: Philippines – Summary of the findings

Scenarios	**LCOE [$/MWh]**	**Total Discounted Cost [$B]**	**CO2 Cumulated [MT]**	**CO2 in 2050 [MT]**
Business-As-Usual	54	605	46368	2909
Scenario A 10% coal to LRs (Optimistic/Conservative)	54 - 55	602 - 622	44178	2617
Scenario B 50% coal to LRs (Optimistic/Conservative)	54 - 62	605 - 699	39750	1723
Scenario C 100% coal to LRs (Optimistic/Conservative)	55 - 71	617 - 796	36475	604
Scenario D 50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	54 - 63	606 - 703	39750	1723

Scenario E 100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	55 - 72	621 - 809	36475	604
Scenario F 100% coal to SMRs (Optimistic/Conservative)	56 - 73	626 - 821	36475	604
Scenario G 100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	59 -87	658 - 977	33960	172
Scenario H 10% coal to Wind (50%) and Solar (50%)	54	608	44005	2615
Scenario I 50% coal to Wind (50%) and Solar (50%)	56	632	39312	1710
Scenario J 100% coal to Wind (50%) and Solar (50%)	61	681	35919	579
Scenario K 100% fossil fuels to Wind (50%) and Solar (50%)	70	783	33356	130

Table A6: Thailand – Summary of the findings

Scenario	**LCOE [$/MWh]**	**Total Discounted Cost [$B]**	**CO2 Cumulated [MT]**	**CO2 in 2050 [MT]**
Business-As-Usual	37	418	30442	1987
Scenario A 10% coal to LRs (Optimistic/Conservative)	37 - 38	416 - 426	29883	1880
Scenario B 50% coal to LRs (Optimistic/Conservative)	37 - 41	415 - 462	27673	1431
Scenario C 100% coal to LRs (Optimistic/Conservative)	38 - 46	422 - 512	26032	871
Scenario D 50% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	37 - 42	416 - 465	27673	1431
Scenario E 100% coal to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	38 - 46	424 - 518	26032	871

Scenario F 100% coal to SMRs (Optimistic/Conservative)	38 - 47	427 - 525	26032	871
Scenario G 100% fossil fuels to LRs (50%) and SMRs (50%) (Optimistic/Conservative)	45 - 78	507 - 875	22522	136
Scenario H 10% coal to Wind (50%) and Solar (50%)	37	420	29818	1878
Scenario I 50% coal to Wind (50%) and Solar (50%)	39	432	27503	1425
Scenario J 100% coal to Wind (50%) and Solar (50%)	41	457	25672	858
Scenario K 100% fossil fuels to Wind (50%) and Solar (50%)	56	632	22061	86