Towards achieving Singapore's carbon emission reduction goals by means of electricity imports

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***Abstract*—This study presents a comparison of pathways to emission reduction in Singapore including its neighbouring countries. Given Singapore's limited renewable resources, electricity imports are one possible pathway to reduce the country's carbon footprint. This study quantitatively shows that restricting greenhouse gas (GHG) emissions in Singapore alone leads to a higher dependence on electricity imports as compared to setting a GHG emission reduction goal for the whole Association of Southeast Asian Nations (ASEAN) which allows for more local power generation from fossil fuels in Singapore. Our findings show that with regional collaboration and infrastructure investment for grid expansion, Singapore can leverage ASEAN's renewable energy resources to meet its targets, enhancing both regional energy security and economic integration. This study aims to provide strategic insights for policymakers on achieving a low-carbon future through regional energy cooperation.**

***Index Terms*—Carbon emission reduction, Energy system modelling, Optimisation, Singapore, ASEAN, Cross-border transmission**

I. Introduction

Climate change poses a great threat to humanity with many adverse effects worldwide. Various nations have pledged to fight climate change by curbing their emissions progressively and achieve carbon neutrality [1], [2]. Though Singapore's share of global GHG emissions is only 0.11 %, the nation has set a goal for its power generation sector to become carbon neutral by 2050. The share of electricity in the total final energy consumption of Singapore is around 25 % [3]. In 2022, around 40 % of Singapore's emissions stemmed from the power sector [4].

Transitioning to cleaner energy is a priority in the ASEAN region as all the ASEAN member states are committed to reducing GHG emissions. The ASEAN Plan of Action for Energy Cooperation (APAEC) aims to enhance energy security and sustainability through increased energy adoption [5]. The region targets a share of 23 % renewable energy of its total primary energy supply by 2025. This collective commitment highlights the potential for regional synergies in achieving significant GHG emission reduction. Developing an ASEAN power grid is one of the essential measures that are able to foster the energy transition in this region.

Energy supply security is a critical concern for Singapore, given its status as a densely populated island nation with limited sources of renewable energy. Consequently, it is a challenge for Singapore to decarbonise its power sector. The government has adopted the "four switches" energy transition policy to address this [6]. These "switches" include natural gas, solar photovoltaics, regional power grids, and low-carbon alternatives (such as "green" hydrogen, nuclear energy or geothermal energy).

This study assesses the possible future power generation mix and electricity import needs under a scenario in which either Singapore or ASEAN must reduce its GHG emissions by 90 % in the power generation sector by 2050 as compared to 2022. In the former case, Singapore will have to reduce its power generation from fossil fuels drastically to achieve this goal, since today, approximately 95 % of Singapore's electricity is generated from fossil-fuelled power stations [7]. In the latter case, Singapore can retain more of its fossil-fuelled generation as other countries with higher renewable energy potentials can compensate for some of Singapore's GHG emissions.

Work on reducing emissions of ASEAN's and Singapore's power generation system has been carried out in numerous previous studies. Stich et al. [8] assessed the economic benefits of cross-border power transmission in ASEAN under a scenario with higher renewable electricity generation. The objective of their model was to minimise generation, transmission and storage costs. The results indicate that electricity trade within ASEAN nations allows for effective utilisation of the region's available renewable energy resources reducing power supply cost and CO_2 emissions. No particular emission targets for the region or any specific countries were set, though. Handayani et al. [9] assessed net-zero emissions pathways for ASEAN using the Low Emissions Analysis Platform (LEAP). Their results indicate that Singapore's 2050

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power renewable electricity generation storage will be key in decarbonising the power sector. However, the study does not incorporate a regional transmission system between the ASEAN nations. As a result of their model, Singapore's 2050 power generation mix will contain nuclear technology instead of clean energy imports. Fahim et al. [10] employed a qualitative technique to evaluate the impact of improved renewable electricity generation on emissions in the ASEAN region. The study recommends various steps to increase renewable energy generation, most of which remains untapped. However, it does not demonstrate how renewable electricity generation can help the ASEAN nations meet their emission reduction targets. Setyawati et al. [11] carried out a Singapore-centric calculation-based analysis to evaluate different decarbonisation pathways. Their study shows how Singapore's power generation mix could evolve by applying different net-zero scenarios. Their results suggest that boosting renewable energy imports enables Singapore's energy resilience and secures a clean energy future. However, it is unclear whether they used any cost optimisation to forecast the future power generation mix. A decarbonisation roadmap for Singapore was presented in [12]. For the power sector, the authors considered carbon capture with the captured CO_2 to be stored in other countries. This technology can help reduce emissions while further relying on fossil generation. Electricity imports were not considered.

The reviewed studies do not outline the intermediate capacity building targets that the ASEAN region should set to meet their decarbonisation goals. Moreover, the published works do not examine how Singapore's power sector might evolve with higher renewable electricity generation in the ASEAN region.

This study addresses the gap in the literature by exploring 90 % carbon emission restriction scenarios at ASEAN and Singapore level by considering the boost in generation from renewable energy resources. The study focuses on how Singapore can meet its decarbonisation targets by 2050 through reliance on renewable energy imports from other ASEAN nations. Scenario-based analysis is a crucial tool in this context, providing a structured framework to navigate uncertainties and complexities inherent in such a transition. Assessing a scenario dominated by renewable energy technologies is important for the following reasons. Firstly, it aids in understanding the feasibility of cross-border renewable energy integration, which is essential for Singapore given its limited renewable energy resources. Secondly, it highlights the potential for regional cooperation in achieving shared sustainability goals, fostering a more resilient and interconnected energy system. Finally, this study assists policymakers in devising better strategies that are adaptable, ensuring that the pathway to decarbonisation is both effective and resilient.

By examining the interplay between Singapore's energy needs and ASEAN's renewable energy potential, this study aims to provide valuable insights into the future power generation mix under a scenario with the future ASEAN grid having a high penetration of renewable energy technologies.

II. Methodology

A. Data collection

To evaluate Singapore's future power generation mix in different scenarios, we first collect electricity supply and demand data for all ASEAN countries from the year 2022. To forecast Singapore's electricity demand, published data of 3 % annual growth in Singapore's electricity demand [13] has been used. Consequently, the projected electricity demand in 2050 amounts to approximately 128 TWh, which is in line with the value reported in [11]. Demand projections for the other ASEAN nations have been taken from [5].

To forecast the electricity supply, we chose 2030, 2040 and 2050 as future modelling years. Myopic optimisation is implemented to optimise the investment planning for the considered modelling years. This means that the model designs a cost-optimal system by considering the emission restrictions defined in the respective modelling year. However, it does not have a perfect foresight of the final modelling year which is 2050 in this study. This approach ensures that along with reaching the emission reduction target by 2050, targets set in the intermediate years are also achieved cost-optimally.

B. Model setup

We used the tool *urbs* [14], a model generator for energy systems. It is capable of optimising the power generation mix by minimising cost or emissions for a single year or for a sequence of years using the outputs of the previous model year for the next model year. *urbs* requires information on commodity prices, power generation, transmission, and time series for demand and intermittent generators as inputs. The cost function is given in Equation (1), where C_{fuel} denotes fuel prices, C_{inv} investment costs, C_{fix} fix costs and C_{var} variable costs for generation. Cost of storage systems and transmission are given by C_{sto} and C_{tra}.

$$C_{total} = C_{fuel} + C_{inv} + C_{fix} + C_{var} + C_{sto} + C_{tra} \quad (1)$$

Fuel costs occur for every unit of fuel used in a generation process, investment costs occur for every MW of generation, storage or transmission built, whereas fixed and variable costs occur per time step. Each generation process has a certain efficiency and produces CO_2 emissions if it burns fossil fuels. This study uses technological investment costs from multiple sources [15], [16], [17] to align the investment cost reduction of renewable energy technologies owing to technological improvements.

The existing installed power generation capacities have been obtained from [18]. Capacity expansion is allowed for each power generation technology, considering its respective technical feasibility. The available potential of renewable energy resources in the region is determined by an open-source tool called pyGRETA [19]. Our estimates indicate that the ASEAN region's renewable energy installations are utilising only 3 % of the available resources, indicating a high potential for capacity expansion. Furthermore, the model addresses the necessity of importing electricity by incorporating cross-border transmission ensuring that Singapore can access exported electricity from neighbouring countries.

This approach to infrastructure planning equips Singapore with the foresight to anticipate future electricity demand and allocate resources cautiously.

C. Scenarios

In this study, the following three distinct scenarios are designed to explore various pathways towards a sustainable energy future for Singapore.

Business-as-usual (BAU) No CO_2 emission restrictions

Singapore restrictions (SR) CO_2 emission restrictions apply to Singapore only.

ASEAN restrictions (AR) CO_2 emission restrictions apply to the whole ASEAN region, not to individual countries.

CO_2 emissions from 2020 are considered as the baseline. In both the AR and the SR scenario, CO_2 emission restrictions are applied to achieve a 20 % reduction by 2030, a 55 % reduction by 2040, and a 90 % reduction by 2050.

III. Results

In this section, we present and analyse the results of our modelling efforts to forecast Singapore's power generation mix in the three scenarios introduced.

As outlined in Section II-A, we used electricity demand data for Singapore from 2022 and projected Singapore's energy demand to 2050. We used *urbs* to obtain the cost-optimal power generation mix for the years 2030, 2040 and 2050 in the three different scenarios presented in Section II-C. Each scenario was assessed for its impact on CO_2 emissions, energy security, and generation costs.

Figure 1 illustrates the total power generation of Singapore and net imported electricity from Malaysia and Indonesia for each scenario. It shows that in the two scenarios with CO_2 emission restrictions, there is a significant increase in energy imports in order to meet the emission reduction targets.

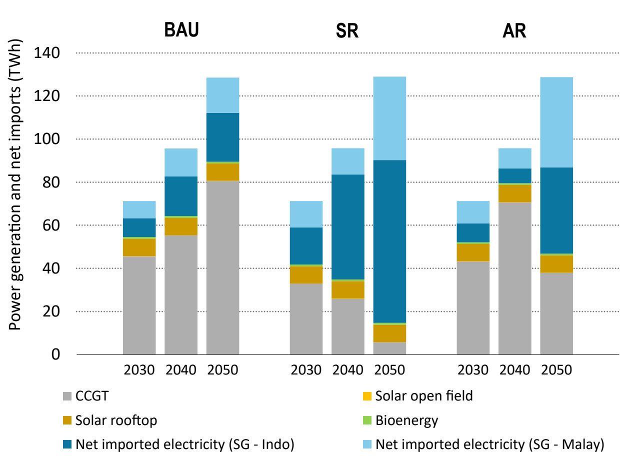

Fig. 1. Power generation mix of Singapore for each scenario in 2030, 2040 and 2050.

The power generation mix of Singapore for the year 2040 in the AR scenario shows an increase in local gas generation and a reduction in net imports. This is due to the fact that in the SR scenario, the neighbouring countries are using generation from coal and gas to meet their own electricity demand and export the electricity generated from renewable sources to Singapore, whereas in the AR scenario, the neighbouring countries use electricity from local renewable technologies, resulting in higher local gas generation in Singapore.

In the SR scenario, the share of net electricity imports in Singapore's 2050 power generation mix increases to 89 % from 64 % in the AR scenario.

The peak demand in 2022 amounts to 7.8 GW. Considering 3 % annual growth [13], Singapore's peak electricity demand will increase to 17.8 GW in 2050 with peak hours typically occurring between 10 a.m. and 4 p.m. To accommodate this increase in demand, our modelling results suggest that expanding the capacity of interconnections between Singapore and neighbouring countries like Malaysia and Indonesia will be essential. Figure 2 illustrates the necessary transmission expansion to facilitate the expected electricity imports.

In our model, we did not allow expansion of cross-country transmission capacity before 2030. For the BAU and the AR scenarios, the model allows Singapore's transmission capacity to be extended by 2 GW in 2030, 6 GW in 2040, and up to 12 GW in 2050. In the SR scenario, Singapore is permitted to expand its transmission capacity by 4 GW in 2030 and 8 GW in each subsequent model year in the SR scenario. This means that in theory, the transmission capacity could be extended up to 20 GW by 2050.

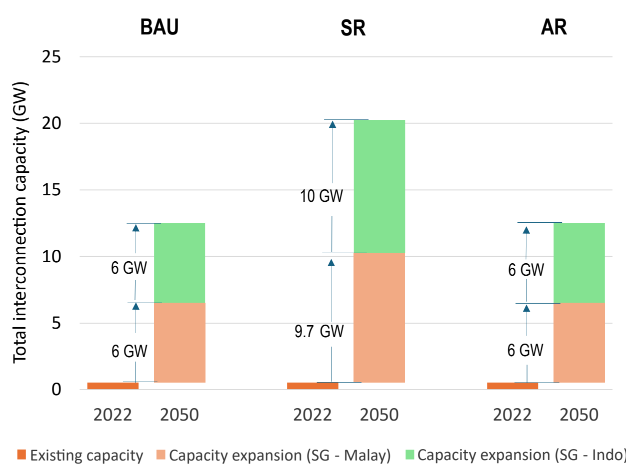

Fig. 2. Expansion of Singapore's power transmission capacity.

As shown in Figure 2, the results indicate that the maximum expansion of combined transmission capacity between Singapore and Malaysia, and between Singapore and Indonesia reaches up to 20 GW in the SR scenario. This significant expansion highlights the reliance on imported electricity due to the high cost of domestic generation with carbon constraints. Conversely, in the AR scenario, the need for imported energy from Malaysia and Indonesia is much lower. In this scenario, the transmission capacity is extended to just about 13 GW as Singapore can generate more of its electricity domestically, while the renewable energy generation in the remaining ASEAN nations is sufficient to meet the overall ASEAN GHG emission restrictions.

IV. Conclusion

This study examined GHG emission reduction pathways in ASEAN with a focus on Singapore's power generation mix. Three distinct scenarios have been defined with varying CO_2 emission restrictions, from no restrictions to restrictions for Singapore alone to restrictions for all of ASEAN.

For a CO_2 emission reduction target of 90 % at Singapore level in 2050 (SR scenario), the net electricity imported by Singapore makes up to 89 % of its electricity demand. The share of electricity generated by local natural gas power stations is reduced to 4 %, while the share of solar generation remains at 6 %.

For a CO_2 emission reduction target of 90 % at ASEAN level in 2050 (AR scenario), the results show that 64 % of Singapore's electricity demand is going to be met by electricity imports from Malaysia and Indonesia, while 30 % is going to be covered by local natural gas power stations, followed by local solar generation contributing to 6 %.

The results clearly show that ASEAN-wide restrictions are favourable for Singapore since the country will be less dependent on imports. Moreover, there could always be sufficient backup capacity in Singapore to ensure security of supply.

In future work, carbon capture will be considered in addition to importing electricity from renewable energies generated in other countries. Moreover, imports of "green" hydrogen for power generation in hydrogen-ready gas power stations will be assessed.

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