Modelling ASEAN's Road Transport Energy Demand and Carbon Emissions Using a Bottom-up Approach

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Abstract**—The final energy consumption of the transport sector of the Association of Southeast Asian Nations (ASEAN) has grown 1.96-fold since 2005. The continuation of historical trends is expected to result in a 2.6-fold increase by 2050 as compared to 2022. This paper analyses the future road transport energy demand of ASEAN by applying a bottom-up approach through the energy demand modelling framework called endemo. The final energy demand is computed for the base year of 2020 and deviates by only 4% from the International Energy Agency (IEA) data. ASEAN's road transport energy demand is expected to increase almost 4-fold in 2050 as compared to 2020 due to economic-driven vehicle population growth without electrification. With the same growth in vehicle population paired with country-level electrification, the energy demand increases by only a factor of 1.2 as compared to the base year. For the same electrification policies without any vehicle growth, that number drops by 36%. A 74% energy demand reduction is expected in 2050 in comparison to 2020 by applying 100% electrification policy across all vehicle types and nations assuming the vehicle population remains constant. Implementing a power generation mix dominated by 90% renewables and large-scale electrification leads to an emission reduction potential of 86%. The results suggest that existing electrification policies may not be sufficient in meeting climate goals. Vehicle population control measures, electrification policies, and a cleaner power generation mix allow for greater carbon emission reduction and extended benefits across the region.**

Keywords - road transport, electrification, energy demand, endemo, linear regression, carbon emission reduction

I. INTRODUCTION

The transport sector constitutes 20% of the world's total carbon emissions. Petroleum products like petrol and diesel when combusted in internal combustion engines (ICE) vehicles emit primarily carbon dioxide.

ASEAN is a group of ten countries located geographically in close proximity to one another which cooperates to achieve political, social and economic prosperity.

Historical data show that final energy consumption of ASEAN's transport sector grew dramatically from 863 TWh in 2005 to 1,689 TWh in 2022 [1] [2]. If historical trends continue, it is expected that this consumption will reach 4,359 TWh by 2050 [2]. Applying regional targets and a carbon neutral system leads to a 50% increase in the energy demand of the traffic sector in 2050 compared to 2022 [2]. Of the transport sector's overall energy consumption, road transport makes up 93.5% in 2022 [2].

Multiple studies have investigated the road transport sector using various methods to estimate the final energy demand and carbon emissions.

Yanfei Li et.al. [3] investigated the road transport sector in ASEAN through various hypothetical electrification scenarios. They found that the final energy consumption would experience a significant rise in a business-as-usual scenario without policy intervention. With 30% EV penetration and higher fuel economy across all countries by 2040, the final energy consumption is expected to drop. The authors acknowledge that emissions would also experience a drop in this scenario, and power sector decarbonization should be coupled with EV policies. While the study provided useful projections, country-level EV policies were unexplored.

In [4], the authors delved into Singapore's road transport sector to estimate the energy demand and emission reduction potential based on data-driven vehicular parameters. Here, the authors assumed 100% electrification of its vehicle fleet based on the government's electrification policy. They estimated the final energy demand and emissions to reduce by 73.60% and 93.64% respectively in 2050 compared to 2020. These estimations come after a switch to 100% electrification and an implementation of a clean power generation mix. The results show promising insights into incorporating climate change policies successfully in a country and the potential of extending this into ASEAN.

Kazancoglu et al. [5] published a study using grey prediction to forecast and evaluate greenhouse gas emissions for the road transport sector in four European nations. The authors then proposed a few countermeasures to decarbonize road transport in those countries: modal shift, fuel efficiency, using alternative fuels, city traffic management, low carbon society, taxation system, and new car types with renewable energy. For energy consumption forecast estimates in Morocco,

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Oubnaki et.al. [6] performed regression analysis using historical energy consumption data along with macroeconomic drivers like gross domestic product (GDP) and population and other demand drivers like vehicle fleet and vehicle evolution. For both studies, policy intervention is seen to be necessary to decarbonize the road transport sector. An extension to these investigations would be to introduce the policies into a bottom-up model to quantify their sensitivities on the final energy consumption and emissions [6].

Krause et.al. [7] investigated some pathways towards carbon reduction for the European road transport sector. The study investigated measures for vehicle efficiency improvements, transport smoothing and reduction, and vehicle fleet electrification through scenario analysis. The results show that there is an emission reduction potential of up to 90% in 2050 compared to 1990 because of electrification of the entire fleet. While this study provided valuable insights into the efficacy of pathways, it did not analyze the impact of country-level electrification on the emission reduction and electricity demand potentials.

The cited literature presents a mix of top-down, bottom-up, and policy-based approaches to analyze the road transport sector. While there are some country-level investigations into this sector, there are limited studies that conduct long-term regional energy demand and emission forecasts which consider the role of electrification and economic-driven vehicle population growth along with different power generation mixes.

This paper aims to address these literature gaps and showcase through the endemo [8] prospective final energy demand and emissions forecast resulting from the road transport sector in the ASEAN region. With this analysis, a multi-pronged approach to tackle climate change in this sector is proposed.

II. METHODOLOGY

The bottom-up method adopted in this paper is through an open-source tool called endemo [8] [9]. It is a framework that allows users to input a series of sector-based data on a country-level which will generate sectorial energy demand forecasts.

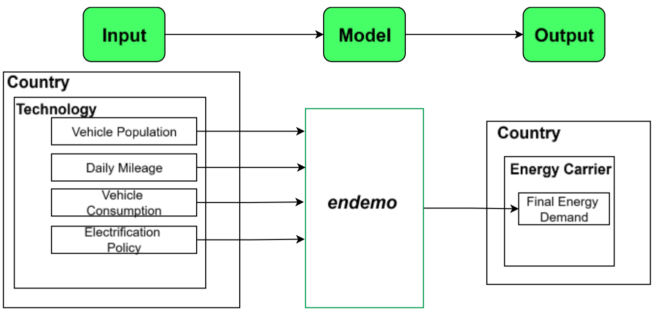

Fig.1. endemo-based road transport model.

This tool numerically processes user inputs and, by applying selected methods and modelling the relationships between variables in the observed consumption sector and their macroeconomic drivers, generates forecasts for these variables and for the final energy demand. A model for the road transport sector for ASEAN is developed and visualized in Fig. 1.

A. Input parameters

Input parameters for the road transport sector are vehicle population, daily mileage, vehicle consumption of ICEVs and EVs, and policy targets regarding electrification of the vehicle fleets. The policy targets of each country are listed in Table 1. There are four formulated scenarios: S1, S2, S3, S4, explained in Section B. Included are road transport vehicles: private cars, motorcycles, taxis, buses, as well as freight traffic vehicles. For each country and vehicle type, the vehicle population, vehicle mileage, and the fuel consumption data for 2020 are displayed in Tables 2 and 3**.** In Singapore, there are also specific vehicle types: private-hire cars (Car_PH), goods-cum-passengers truck (Truck_GP), light-goods trucks (Truck_LG), heavy-goods trucks (Truck_HG), very heavy-goods trucks (Truck_VHG) single-deck (SD), double-deck (DD), and articulated buses (AB). In Table 3, the subscripts under the vehicle column indicate the fuel type, either petrol (P) or diesel (D).

TABLE 1. ASEAN ROAD TRANSPORT ELECTRIFICATION POLICIES.

Country	Vehicle	S2 and S3		
		Target (%)	Year	Source
Brunei	Car, Taxi, Truck, Bus, Motorcycle	60.0	2035	[10]
Cambodia	Car	40.0	2050	[10]
Cambodia	Motorcycle	70.0	2050	[10]
Indonesia	Bus	100.0	2050	[11]
Indonesia	Motorcycle	10.0	2030	[10]
Indonesia	Car	11.1	2030	[10]
Laos	All	30.0	2050	[12]
Malaysia	Car, Taxi, Truck, Bus, Motorcycle	80.0	2050	[13]
Myanmar	-	-	-	-
Philippines	Motorcycle, Car	10.0	2040	[10]
Singapore	All	100.0	2040	[14]
Thailand	Car	30.0	2035	[10]
Thailand	Truck	30.0	2035	[10]
Vietnam	All	100.0	2050	[15]

TABLE 2. INPUT PARAMETERS: VEHICLE POPULATION & MILEAGE PER DAY.

Country	Vehicle	Vehicle Population	Vehicle Mileage (km/day)
Brunei	Car	267,490 [16]	48.00 [16]
	Taxi	165,000 [16]	70.00 [17]
	Truck	8,320 [16]	110.00 [16]
	Bus	8000 [16]	52.00 [16]
	Motorcycle	5000 [16]	13.23 [16]
Cambodia	Car	89,000 [16]	48.00 [16]
	Taxi	4,000 [16]	70.00 [17]
	Truck	16,270 [16]	191.70 [18]
	Bus	2,830 [16]	130.00 [18]
	Motorcycle	540,000 [16]	50.00 [17]
Indonesia	Car	15,592,000 [16]	37.26 [17]
	Truck	5,022,000 [16]	137.00 [17]
	Bus	232,000 [16]	220.00 [16]
	Motorcycle	6,528,000 [16]	50.00 [17]
Laos	Car	145,320 [16]	48.00 [16]
	Truck	63,300 [16]	191.70 [18]
	Bus	65,960 [16]	200.00 [16]
	Motorcycle	1,697,380 [16]	13.23 [16]
Malaysia	Car	14,695,660 [16]	65.80 [17]
	Taxi	92,000 [16]	70.00 [17]
	Truck	1,295,490 [16]	191.70 [18]
	Bus	62,970 [16]	130.00 [18]
	Motorcycle	14,322,230 [16]	50.00 [17]
Myanmar	Car	563,930 [16]	35.35 [19]
	Taxi	135,000 [16]	70.00 [19]
	Truck	412,420 [16]	191.70 [19]
	Bus	30,640 [16]	130.00 [19]
	Motorcycle	6,069,300 [16]	13.23 [16]
Philippines	Car	1,413,790 [16]	54.79 [17]
	Taxi	26,000 [16]	137.00 [17]
	Truck	475,000 [16]	191.70 [18]

Country	Vehicle	Vehicle Population	Vehicle Mileage (km/day)
	Bus	37,000 [16]	220.00 [17]
	Motorcycle	8,014,000 [16]	50.00 [17]
Singapore	Car	519,132 [20]	47.95 [21]
	Car_PH	114,910 [20]	230.00 [22]
	Taxi	15,678 [20]	
	Truck_GP	2,798 [20]	109.59 [23]
	Truck_LG	94,211 [20]	109.59 [23]
	Truck_HG	27,307 [20]	109.59 [23]
	Truck_VH	16,467 [20]	109.59 [23]
	Bus_SD	3,805 [23]	201.55 [23]
	Bus_DD	1,629 [23]	
	Bus_AB	430 [23]	
	Bus	18,912 [20]	201.55 [21]
	Motorcycle	142,453 [20]	35.62 [21]
Thailand	Car	19,481,780 [16]	48.00 [16]
	Taxi	118,000 [16]	168.70 [18]
	Truck	1,149,670 [16]	85.21 [18]
	Bus	165,000 [16]	173.20 [18]
	Motorcycle	17,281,440 [16]	13.23 [16]
Vietnam	Car	2,429,600 [16]	48.00 [16]
	Taxi	56,000 [16]	70.00 [17]
	Truck	1,422,160 [16]	137.00 [17]
	Bus	183,500 [16]	130.00 [18]
	Motorcycle	72,061 [16]	50.00 [17]

TABLE 3. INPUT PARAMETERS: FUEL CONSUMPTION, ELECTRICITY DEMAND.

Country	Vehicle	ICE Vehicle fuel consumption (litre/100km)	EV electricity demand (Wh/km)
Brunei	Car P	7.60 [24]	166.00 [25]
	Taxi P	7.60 [24]	
	Truck D	7.77 [25]	277.00 [25]
	Bus D	50.00 [23]	1,600.00 [23]
	Motorcycle P	1.90 [26]	50.00 [25]
Cambodia	Car P	7.60 [24]	166.00 [25]
	Taxi P	7.60 [24]	
	Truck D	8.94 [23]	277.00 [25]
	Bus D	50.00 [23]	1,600.00 [23]
	Motorcycle P	1.90 [26]	50.00 [25]
Indonesia	Car P	7.20 [25]	166.00 [25]
	Car D	8.57 [25]	
	Truck D	7.77 [25]	277.00 [25]
	Bus D	50.00 [23]	
	Motorcycle P	1.90 [26]	50.00 [25]
Laos	Car P	7.20 [25]	166.00 [25]
	Car D	8.57 [25]	
	Truck D	8.94 20]	277.00 [25]
	Bus D	8.94 [23]	277.00 [25]
	Motorcycle P	1.90 [26]	50.00 [25]
Malaysia	Car P	7.20 [25]	166.00 [25]
	Taxi P		
	Truck D	7.77 [25]	277.00 [25]
	Bus D	8.94 [23]	277.00 [25]
	Motorcycle P	1.90 [26]	50.00 [25]
Myanmar	Car P	7.20 [23]	166.00 [25]
	Taxi P		
	Truck D	8.94 [23]	277.00 [25]
	Bus D	8.94 [23]	
	Motorcycle P	1.90 [26]	50.00 [25]
Philippines	Car P	6.10 [23]	166.00 [25]
	Taxi P		
	Truck D	7.77 [25]	277.00 [25]
	Bus D	50.00 [23]	1,600.00 [23]
	Motorcycle P	1.90 [26]	50.00 [25]
Singapore	Car P	7.60 [24]	166.00 [25]
	Car_PH P	3.70 [25]	115.00 [26]
	Car_PH D	6.10 [25]	
	Truck_GP D	7.77 [25]	277.00 [25]
	Truck LG D	8.94 [23]	277.00 [25]
	Bus_SD D	50.00 [23]	1,600.00 [23]
	Bus_DD D	55.00 [23]	2,300.00 [23]
	Bus_AB D	60.00 [23]	2,500.00 [23]
	Motorcycle P	1.90 [26]	50.00 [25]
Thailand	Car P	7.20 [25]	166.00 [25]
	Taxi P	7. 60 [24]	
	Truck D	7.77 [25]	277.00 [25]
	Bus D	8.94 [23]	1,600.00 [23]
	Motorcycle P	1.90 [26]	50.00 [25]
Vietnam	Car P	7.60 [24]	166.00 [25]
	Taxi P	7.52 [24]	166.00 [25]
	Truck D	7.77 [25]	277.00 [25]
	Bus D	8.94 [23]	277.00 [25]
	Motorcycle P	1.90 [26]	50.00 [25]

B. Scenarios

Four scenarios are formulated and listed as follows:

S1: vehicle population growth, no policy implementation

S2:vehicle population growth, with policy implementation

S3: no vehicle population growth, with policy implementation

S4: no vehicle population growth, with optimistic electrification (100%)

Defined are the target electrification rate and the year in which the target is achieved. If the target year is before 2050, the electrification rate between the target year and 2050 remains constant. The development from 2020 till the target year is linear, starting from the current electrification rate. Electrification policies for Myanmar were not found, hence, not applied for that nation. Vehicle drivetrain efficiencies are assumed to experience no improvements in ASEAN until 2050.

C. Carbon emissions calculation

The drive-cycle carbon emissions (c_{year}), in tonnes of CO_2 of a given vehicle is expressed as the product of the emission factor (e^f) in $kgCO_2/MWh$, and fuel type, f (petrol, diesel, electricity), and the final energy demand (E^f_{year}) in MWh (Eq. 1). The emission factors for petrol and diesel vehicles are 0.235 $kgCO_2/MWh$ and 0.249 $kgCO_2/MWh$ [4] respectively. The emission factors considered are listed in Table 4.

$$c_{year} = e^f \, . \, E^f_{year} \tag{1}$$

TABLE 4. EMISSION FACTORS OF ENERGY SOURCES

Energy Source	Emission Factor ($kgCO_2/kWh$)
Fossil Fuel	0.820 [4]
Hydro	0.024 [27]
Geothermal	0.038 [4]
Solar	0.020 [4]
Wind	0.011 [28]
Biomass	0.681 [29]
Tidal and Wave	0.037 [30]
Nuclear	0.012 [4]

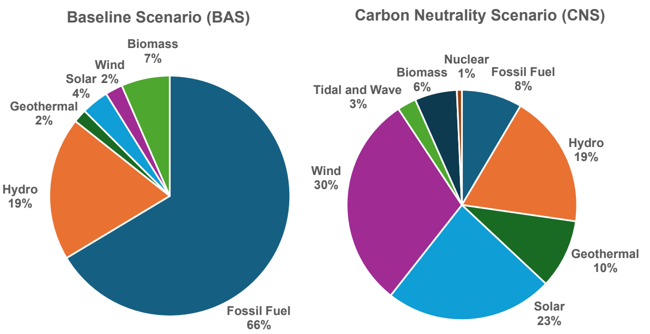

Fig. 2. Power generation mixes in the 8th ASEAN Energy Outlook [2].

In the 8th ASEAN Energy Outlook [2], the power generation mixes seen in Fig. 2 were presented, each representing one scenario stated in the report: Baseline Scenario (BAS) and Carbon Neutrality Scenario (CNS). The power generation mix

in BAS and CNS is dominated by 66.4% fossil fuels and 90.9% renewables, respectively.
Furthermore, electricity imports are seen as a pathway to potentially reduce a country's carbon footprint with regional energy cooperation amongst nations [31].

III. RESULTS AND DISCUSSION

A. Comparison with IEA's energy data (2020)

Based on 8th ASEAN Energy Outlook, 93.5% of total ASEAN transport demand stems from road transport [2]. To the authors' knowledge, road transport energy demand specifically is not reported in literature. To verify the accuracy of endemo's outputs, the aggregated energy demand for all considered energy carriers in 2020 is benchmarked against 93.5 percent of the transport sector's energy demand as published by the IEA for that year [32]. The comparison for each country is presented in Fig. 3 [2]. On an aggregated level for ASEAN, endemo achieves 96% agreement with the IEA statistics, giving a good starting point for future projections.

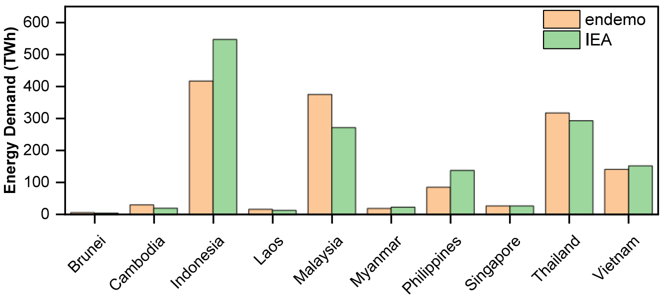

Fig. 3. Country-wise verification of the road traffic final energy consumption estimation for year 2020– endemo and IEA [32].

B. Forecast of vehicle population using uni-variate linear regression (UVLR)

The forecasts for each country's vehicle population (Fig. 4) are generated by applying UVLR which analyzes the correlation between each country's single independent variable - GDP per capita in local currency of each nation (g_1), with a dependent variable - vehicles per 1000 people (V_{1000}), in time, t. Two conditions are required for the correlation to be quantified as strong: correlation coefficient $r^2 > 0.80$ and statistical significance coefficient $p < 0.05$. With the conditions met, the coefficients (m_1 and c) form Eq. 2.

The vehicle population forecast for each year is computed as the product of V_{1000} and human population forecast, p (Eq. 3).

$$V_{1000}(t) = m_1\, g_1(t) + c \quad (2)$$

$$V(t) = V_{1000}(t) \,.\, p\,(t) \quad (3)$$

GDP per capita projections are derived from multiple sources (Table 4). Average historical GDP per capita growth rates are used wherever these projections were not found. The human population forecasts are taken from the United Nations [33].

Singapore's vehicle population growth is assumed to be 0% since the government puts a cap on most of its road transport vehicles to regulate traffic and ease congestion in the land-constrained country [34].

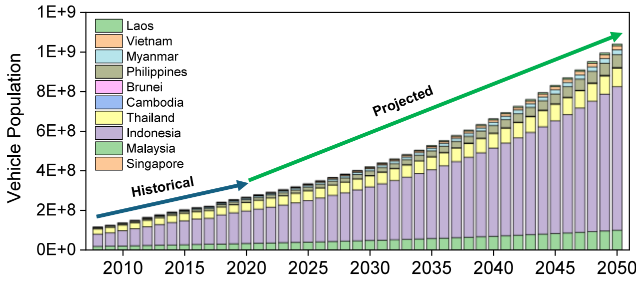

Fig. 4. Vehicle population forecasts generated by UVLR.

TABLE 5. GDP PER CAPITA GROWTH RATE ASSUMPTIONS UNTIL 2050.

Country	GDP per capita growth rate per year (%)	Source
Brunei	2.0	Historical
Cambodia	4.0	Historical
Indonesia	4.9	[35]
Laos	4.0	[36]
Malaysia	3.8	[36]
Myanmar	3.3	Historical
Philippines	4.8	[36]
Singapore	4.4	Historical
Thailand	3.0	[36]
Vietnam	5.6	[36]

C. Final energy demand forecasts

S1 shows that the final energy demand would increase almost 4-fold to 5,387 TWh in 2050, primarily driven by vehicle population growth and the absence of an electrification policy (Fig. 5). This scenario allows non-renewables such as petrol and diesel to dominate the energy usage in this sector (Fig. 6) and thereby continuing to emit greenhouse gases into the atmosphere.

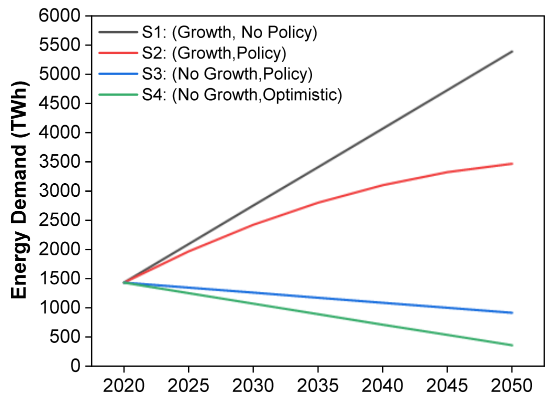

Fig. 5. endemo-based energy demand forecast comparisons across scenarios.

With the successful intervention of country-level electrification policies paired with vehicle population growth in 2050 seen in S2, the energy demand increase is stemmed significantly in comparison to S1 and is expected to reach 3,471 TWh. S2 serves as a potentially realistic situation since actual country-level policies are used in the model. In 2050, the share of electrification will reach approximately one fifth of the total energy demand (Fig. 6). Based on the results, policies referenced in Table 1 may not be sufficient to reach net-zero targets.

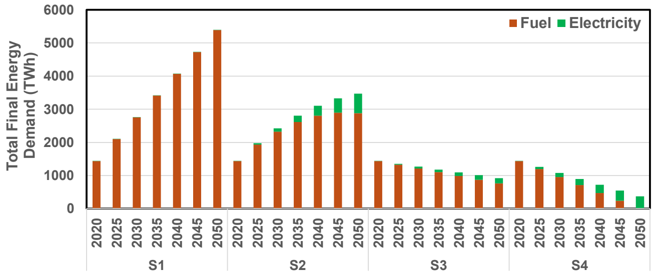

Fig. 6. Energy demand forecasts by scenarios with fuel shift.

Assuming a stagnation in vehicle population growth and country-level electrification policies implemented (S3), demand will drop by 36% in 2050 in comparison to 2020. With a constant vehicle population trajectory into the future, non-renewable sources will experience a drop in consumption, but electricity will still form only 18% of the total energy consumption, further emphasizing that more needs to be done to encourage the shift toward electrification.

Implementing 100% electrification policy across all countries (S4), the energy demand significantly drops by 74% to 369 TWh compared to 2020, depicting the maximal potential energy demand reduction and environmental benefits while keeping the current vehicle population constant.

From the scenarios, it is evident that stemming the vehicle population growth contributes to reducing final energy consumption. Restricting the vehicle population growth across the region almost halve the final energy demand. This is evident across most countries. For countries like Singapore with a growth rate of zero for cars and motorcycles, limited vehicle population growth and successful electrification policy work well in tandem in stemming the energy demand in the future.

Fig. 6 displays the final energy demand forecast results by country. In S1, Vietnam will experience the largest energy demand spike in 2050 (six-fold) as compared to 2020, followed by Myanmar and Laos. These rises are tied to the respective growth rates in the vehicle population growth and absence of an electrification policy. Thailand will experience the second smallest increase in the energy demand in S1, mainly due to saturation in vehicle population growth.

In S2, Singapore and Brunei will experience the highest reduction in demand of 67.4% and 35.0% respectively. This is likely indicative that the electrification policies have a bigger effect on the energy demand than the vehicle population growth restriction does.

In S3, the final energy demand reduction range achieved was 11.6% to 77.2%. Vietnam, Singapore, Malaysia, achieved the highest reductions at 77.2%, 68.1%, and 58.3% respectively. Despite having the largest vehicle population growth forecast, Vietnam's 100% electrification policy will curb the energy consumption eventually in 2050.

In S4, the final energy demand reduction ranges from 68.1% to 81.7%, the highest amongst the four scenarios. This is due to the large-scale electrification in the region.

A 2022 study conducted by [37] used the Low Emissions Analysis Platform (LEAP) to investigate the effects of EVs on the road transport and electricity sectors for Thailand. The deviation between endemo and LEAP-based energy demand estimates for 2020 was found to be around 8%.

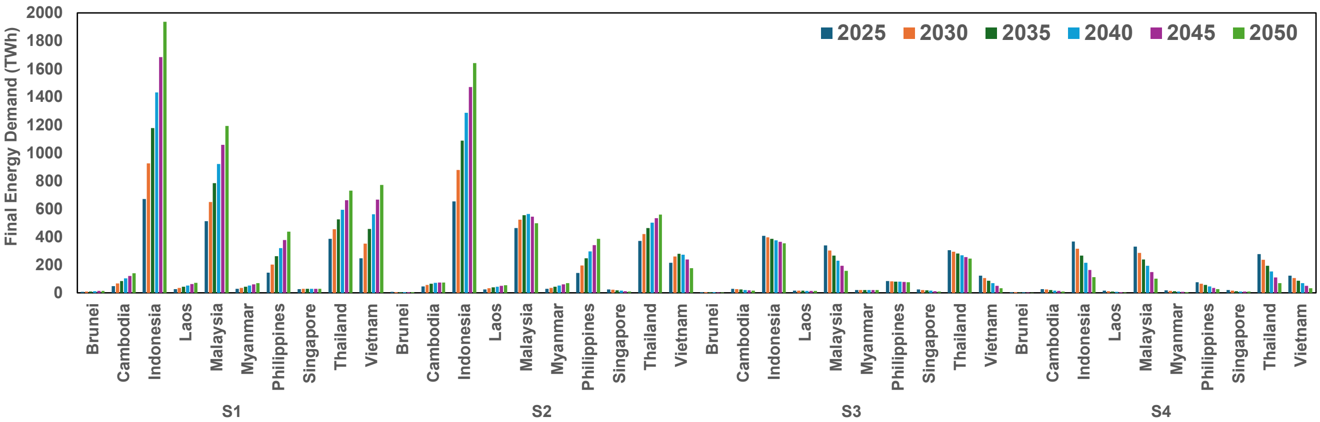

Fig. 7. Energy demand forecasts by scenarios by country.

D. *Carbon emission projection*

The carbon emissions forecasts are visualized on Fig. 8. In S1, emissions continue to grow despite the introduction of renewable energies in the power generation mix due to the rise in vehicle population and absence of electrification, increasing almost 4-fold from 2020 to 2050. With vehicle population growth and country-level electrification implemented in S2, the emissions rise at a slower rate, influenced by the introduction of renewables in the power generation mix.

In S3, the emissions are projected to drop by 41% in 2050 from 2020 with the country-level policies and renewable-dominated power generation, suggesting that the electrification policies are insufficient to reduce emissions significantly. With 100% electrification and cleaner power generation mix in S4, the emission reduction potential reaches 86% in 2050 compared to 2020. Table 6 summarizes the results across the four scenarios for 2050.

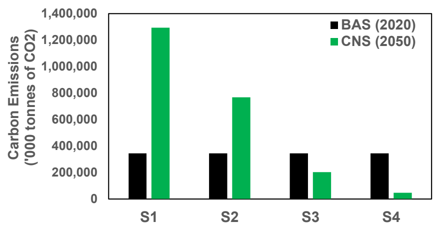

Fig.8. Projected carbon emissions in ASEAN in 2020 and 2050.

TABLE 6. SUMMARY OF RESULTS FROM S1 TO S4 FOR 2050.

Scenario	2050 final energy demand (TWh)	2050 carbon emissions (kilotonnes of CO_2)	Carbon emission change vs 2020 (%)
S1	5,387	1,292,761	274
S2	3,471	766,843	122
S3	923	203,189	- 41
S4	370	47,301	-86

IV. CONCLUSION

The modeling tool endemo was used to forecast the final energy demand of the road transport sector in ASEAN. The energy demand was calculated for 2020 (1,439 TWh) and was found to be 96% in agreement with IEA. Four scenarios were devised to determine the sensitivity of different vehicle population growth and electrification policies. In S1, the energy demand will rise to 5,387 TWh in 2050, dominated by petrol and diesel vehicles. In S2, the energy demand reaches 3,471 TWh. In S3, it is curtailed to 923 TWh. The energy demand reduces to 370 TWh in 2050 with full electrification in S4. Introducing a renewable-dominated power generation mix in S2 reveal emissions would reduce by 41% and 86% in S4 compared to 2020. The energy demand and emission results potentially indicate that the electrification policies are inadequate to allow electricity to dominate the energy mix by 2050 and make significant progress toward a net-zero world. Effective emission reduction in the road transport sector necessitates policy interventions and vehicle growth control, alongside the integration of renewable energy carriers in the power sector.

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