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Emission Reduction Potential of Energy from Biomass Residues in Southeast Asia's Road Transport

Srikkanth Ramachandran, M.Sc.

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Vorsitzender:

Prof. Dr.-Ing Matthias Gaderer

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Prof. Dr. rer. nat. Thomas Hamacher

Prof. Dr. rer. nat. Ulrich Stimming

Prof. Dr.-Ing Ulrich Wagner

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Abstract

Association of Southeast Asian Nations (ASEAN) primarily comprises of rapidly developing countries. The region has been experiencing accelerated economic growth in recent times which has caused a surge in its transport needs. This in turn has steeply increased the emissions from the transport sector.

This thesis begins by identifying the suitable alternatives for decarbonising road transportation in ASEAN. Since most ASEAN countries depend primarily on fossil fuels for electricity production, electrification of transport using the grid does not seem to be the most ideal alternative. Hydrogen also does not seem to provide a long-term sustainable solution due to its inability to include renewable energy at high efficiency. As agriculture plays a major role in most ASEAN economies, powering road transport with energy derived from agricultural residues might help reduce its greenhouse gas (GHG) emissions. Hence, it was decided to estimate the emission reduction potential of bio-energy derived from biomass residues in ASEAN's road transport sector.

To evaluate the same, a model was developed to estimate the emissions of road transport in ASEAN. For this model, an extensive data collection of vehicle types, population, mileage, etc. for every ASEAN country was done. Following this, another model was built to estimate the availability of biomass residues and their locations. Then, the pathways of bio-energy recovery, their emissions and efficiencies were identified. The bio-energy needs of the transport sector for different levels of bio-energy penetration was estimated. Finally, the emission mitigation potential of bio-energy in ASEAN's road transport was assessed.

The total emissions from road transport in ASEAN was estimated to be 346 million tonnes of CO_2 eq., with Indonesia, Thailand and Malaysia being the major contributors (70%). The distribution of emissions by vehicle varies widely between different countries. Passenger cars were the major emitters in Singapore, Malaysia, and Brunei, whereas motorcycles dominated the emissions in Indonesia, Vietnam, and Cambodia. The total energy available from biomass residues in ASEAN was estimated to be 1089 TWh with Indonesia, Thailand, and Vietnam accounting for about 70% of them. Rice straw, Sugarcane trash, logging residues, rice husk, maize stalk and empty fruit bunches of oil palm are the critical residues available in ASEAN.

Based on the feedstock available, the bio-energy products that could be used in transport were identified to be bio-electricity and bio-ethanol. In terms of emissions of energy recovery from biomass, it was found that large, centralised powerplants perform better than small, decentralised ones. Almost all countries except Singapore, Malaysia and Brunei can supply the bio-electricity or bio-ethanol needs of transport (for the different scenarios of bio-energy penetration) with locally available bio-residues. Bio-electricity and bio-ethanol can help reduce the GHG emissions of transport by 72% and 43% respectively. Indonesia, Thailand, and Vietnam benefit the most in terms of absolute reduction in emission for both bio-electricity and bio-ethanol scenarios. Both bio-electricity and bio-ethanol perform better than electrification using existing grid electricity in terms of GHG emission reduction.

Zusammenfassung

Association of Southeast Asian Nations (ASEAN) besteht hauptsächlich aus sich schnell entwickelnden Ländern. Die Region erlebt hat schnelles Wirtschaftswachstum in der letzten Zeit, die ein Wachstum in ihrem Transportbedarf verursacht hat. Dies hat wiederum die Emissionen aus dem Verkehrssektor stark erhöht. Diese Arbeit beginnt mit der Ermittlung der geeigneten Alternativen zur Dekarbonisierung des Straßenverkehrs in ASEAN. Da die meisten ASEAN-Länder bei der Stromerzeugung hauptsächlich auf fossile Brennstoffe angewiesen sind, scheint die Elektrifizierung des Verkehrs über das Stromnetz nicht die idealste Alternative zu sein. Wasserstoff scheint auch keine langfristige nachhaltige Lösung zu sein, da es nicht möglich ist, erneuerbare Energien mit hoher Effizienz einzubeziehen. Da die Landwirtschaft in den meisten ASEAN-Volkswirtschaften eine wichtige Rolle spielt, könnte die Stromversorgung des Straßenverkehrs mit Energie aus landwirtschaftlichen Rückständen dazu beitragen, die Treibhausgasemissionen (THG) zu senken. Daher wurde beschlossen, das Emissionsminderungspotenzial von Bioenergie aus Biomasserückständen im Straßenverkehrssektor der ASEAN abzuschätzen.

Um dies zu bewerten, wurde ein Modell entwickelt, um die Emissionen des Straßenverkehrs in ASEAN abzuschätzen. Für dieses Modell wurde eine umfangreiche Datenerfassung von Fahrzeugtypen, Bevölkerung, Kilometerstand usw. für jedes ASEAN-Land durchgeführt. Anschließend wurde ein weiteres Modell erstellt, um die Verfügbarkeit von Biomasserückständen und deren Standorte abzuschätzen. Dann werden die Wege von Bio-Energierückgewinnung, ihre Emissionen und Effizienz wurden identifiziert. Der Bioenergiebedarf des Verkehrssektors für unterschiedliche Niveaus der Bioenergiedurchdringung wurde geschätzt. Schließlich wurde das Emissionsminderungspotenzial von Bioenergie im Straßenverkehr der ASEAN bewertet.

Die Gesamtemissionen aus dem Straßenverkehr in ASEAN wurden auf 346 Millionen Tonnen CO_2-Äquivalente geschätzt, wobei Indonesien, Thailand und Malaysia die Hauptverursacher sind (70%). Die Verteilung der Emissionen nach Fahrzeugen ist in den verschiedenen Ländern sehr unterschiedlich. Personenkraftwagen waren die Hauptemittenten in Singapur, Malaysia und Brunei, während Motorräder die Emissionen in Indonesien, Vietnam und Kambodscha dominierten. Die Gesamtenergie, die aus Biomasse-Rückständen in ASEAN verfügbar ist, wurde auf 1089 TWh geschätzt, wobei Indonesien, Thailand und Vietnam etwa 70% davon ausmachen. Reisstroh, Zuckerrohrmüll, Holzabfälle, Reisschalen, Maisstängel und leere Fruchtbüschel Ölpalme sind die kritischen Rückstände, die in ASEAN verfügbar sind.

Basierend auf dem verfügbaren Ausgangsmaterial wurden die Bioenergieprodukte, die für den Transport verwendet werden könnten, als Bioelektrizität und Bioethanol identifiziert. In Bezug auf die Emissionen der Energierückgewinnung aus Biomasse wurde festgestellt, dass große, zentralisierte Kraftwerke eine bessere Leistung erbringen als kleine, dezentralisierte Kraftwerke. Fast alle Länder außer Singapur, Malaysia und Brunei können den Bio-Strom- oder Bio-Ethanol-Transportbedarf (für die verschiedenen Szenarien der Bioenergie-Penetration) mit lokal verfügbaren Bio-Rückständen versorgen. Bioelektrizität und Bioethanol können dazu beitragen, die Treibhausgasemissionen des Verkehrs um 72% bzw. 43% zu senken. Sowohl Bioelektrizität als auch Bioethanol sind hinsichtlich der Reduzierung der THG besser als die Elektrifizierung mit vorhandenem Netzstrom.

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1 Introduction

1.1 Overview on climate change

Climate change is a daunting challenge that humankind faces in the 21st century. The chief driver for climate change is global warming [1]. Global warming is the increase in the combined temperature of surface air and sea surface averaged over the globe over a 30-year period [2]. Global warming causes many adverse impacts such as average air and ocean temperature increase, average sea level rise, water and carbon cycle disruption, climate pattern alteration, etc [3]. Intergovernmental Panel on Climate Change (IPCC) has identified the human influence on climate to be the main cause for global warming [2]. Main reason for the rise in average global temperatures is the emission of greenhouse gases (GHG) caused by human activity.

Though the terms 'climate change' and 'global warming' are used interchangeably, in a strict sense, they refer to slightly different things. Global warming refers to the long-term warming of the planet. Climate change is a collective term that encompasses global warming and a broader range of other issues such as rising sea levels, melting mountain glaciers and polar ice caps, shifts in plant blooming patterns, etc. [1]. The climate change has a direct impact on ocean and freshwater ecosystem, water and food supply, human health, human livelihood, etc.

1.1.1 Drivers of global warming

Radiative forcing, also known as climate forcing, is the difference between the radiation that reaches the earth from sun (insolation) and the radiation that is emitted back into the space by earth. This balance between the absorbed and radiated energy is what that determines the average global temperature. This balance is influenced by various factors such as the intensity of insolation, reflectivity of clouds, heat trapping capacity of the atmospheric gases, etc. Gases that trap heat in the atmosphere are known as greenhouse gases. The presence of greenhouse gases (water vapour, CO_2, methane, ozone) is what that keeps the planet at the temperature comfortable for our survival.

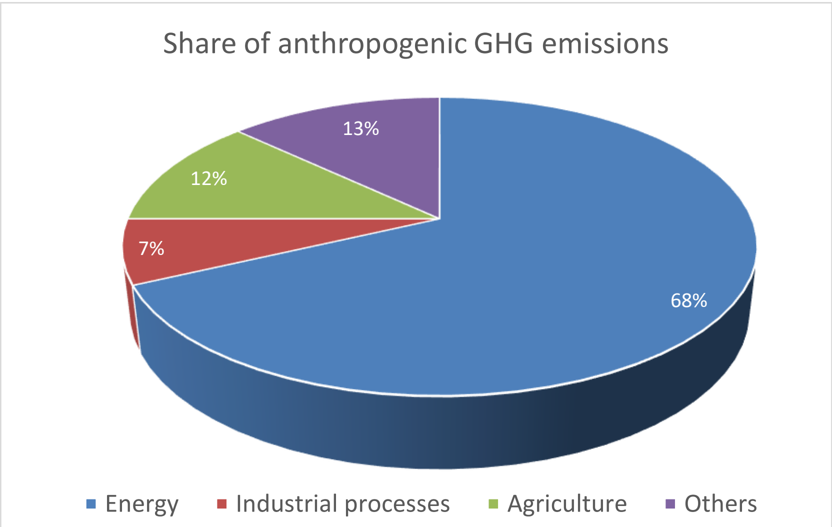

Figure 1.1: Shares of different activities to anthropogenic emission of GHGs

However, the recent industrial revolution which largely fossil fuel dependent, is pumping CO_2 into our atmosphere at very high rates. Climate scientists have observed the CO_2 concentrations in the atmosphere to increase from 280 parts per million in pre-industrial era to 403 parts per million in 2016 [4]. This has led to a global warming of approximately 1°C. Figure 1.1 shows the different human activities and their share in global anthropogenic GHG emissions [4]. The largest contribution (68%) comes from the energy sector. The emission of energy sector accounts for the GHGs emitted by the combustion of fossil fuels. Combustion of fossil fuel releases carbon that has been trapped under the earth, into the atmosphere.

Contributions from different sectors towards the CO_2 emissions arising from fuel combustion is shown in Figure 1.2. The main contribution (42%) comes from electricity and production due to its high dependence on fossil fuels. The transport sector nearly contributes to a quarter of global CO_2 emissions arising from fuel combustion. About 75% of the emissions from transport sector comes from road transport (with the remaining 25% coming from aviation, navigation, etc.). In its present form, almost the entire transport sector is dependent on internal combustion engines (ICE) that use fossil fuels (primarily diesel and petrol) for their propulsion. Hence transport sector has a high carbon footprint. Between 1990 and 2015, the CO_2 emissions from transport sector grew by 68% [4].

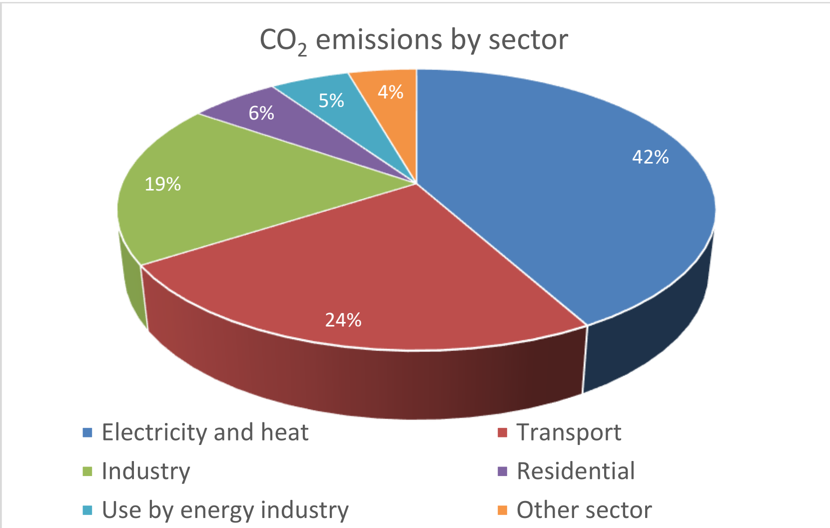

Figure 1.2: CO_2 emissions classified by sector

1.1.2 Necessity for transport emission mitigation

Economic development is strongly coupled with transportation [5]. Trade is an important part of economic growth and trade heavily depends on transport. Even in ancient times, there has been an interdependence between the degree of economic growth and shipping activity. The civilizations that exploited the waterways for transport have had quicker economic growth. This extends to modern day too. Transport not only aids in economic growth, but also leads to social benefits, and improves the standard of living of people. Like transport, energy use for electricity and heat production also has a strong correlation with economic growth [6], [7] and quality of life [8], [9]. Hence, both the sectors are expected to grow steeply soon. Especially in Southeast Asia, which comprises majorly of developing nations, the growth rates of transport and electricity sector is expected to be high.

As observed before, both electricity and transport sectors are major contributors of global GHG emissions. Hence, if no mitigation strategies are implemented, the GHG emissions will continue to grow at a strong rate. It is estimated that if warming continues at the present rate, a global warming level of 1.5°C (above pre-industrial levels) will be reached by about 2040. Further increases in GHG emission rates will cause more warming and create long-lasting changes on various components of the climate system. Climate models predict that the increasing magnitudes of warming shall cause an increase in the likelihood of severe, pervasive and irreversible impacts on people, species and ecosystems. It would adversely impact biodiversity, ecosystem services, economic development and amplify the risks for food and human security [3]. Hence it is imperative to develop CO_2 emission mitigation strategies urgently, especially from energy use.

1.2 A brief overview of ASEAN

Association of Southeast Asian Nations (ASEAN) is constituted by ten nations, viz. Brunei (BRN), Indonesia (IDN), Cambodia (KHM), Laos (LAO), Malaysia (MYS), Myanmar (MMR), Philippines (PHL), Singapore (SGP), Thailand (THA) and Vietnam (VNM). It has been experiencing rapid economic growth in the recent past. As seen from Figure 1.3 the GDP grew by 3.4 times between 1990 and 2015 [10]. The global share of ASEAN's GDP grew from 2% to 3.5% in the same period. Since it comprises of a mix of developing and developed nations, the growth rate varied from one nation to the other. As seen previously, strong economic growth is coupled with a strong growth in energy consumption (for electricity production and transport, etc.). The primary aim of this thesis is to identify methods to mitigate greenhouse gas emissions from transport sector in ASEAN.

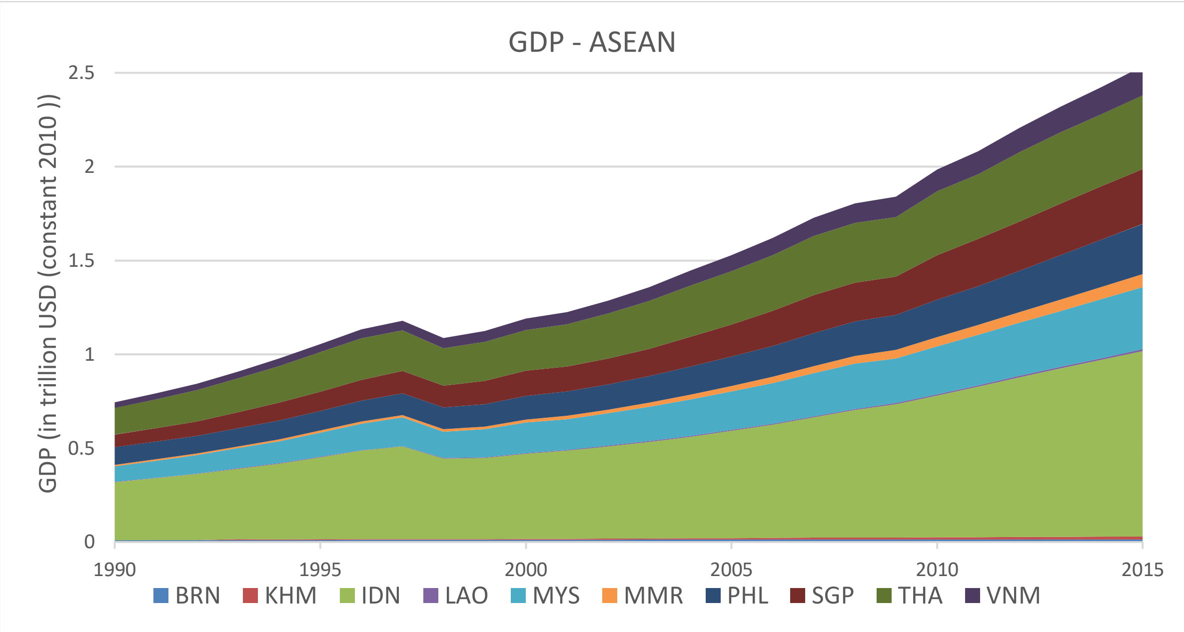

Figure 1.3: GDP in ASEAN between the years 1990 and 2015, expressed at constant 2010 USD

With respect to electricity and heat generation, the main mitigation strategy is to increase the share of primary energy from renewables (including solar, wind, bio-energy, hydro, etc.). Strategies also call for a shift in the fossil fuel mix, with the supply from coal decreasing and the supply from natural gas increasing. Carbon capture and storage is another technology being considered. However, mitigation of emissions from electricity production is beyond the scope of this Thesis. The work of Juergen Stich [11] has analysed the potential of renewable energy and its emission mitigation in ASEAN at great depths. The focus of this work lies with road transport. This thesis shall look at the alternatives that are available for decarbonising road transport in general. And initial assessment of the alternatives will be done. Then the energy situation in ASEAN shall be explored. Based on the assessment of alternatives and the energy availably in ASEAN, the necessary thesis questions will be formulated. The overall structure of the Thesis is discussed at the end of the next chapter.

2 Road transport decarbonisation – identification of alternatives relevant for ASEAN

This chapter aims at identifying the alternatives that are suitable for road transport decarbonisation in ASEAN. The existing global climate change issues, and the contribution of transport sector towards the same was discussed in the introduction. The alternatives that are available for reducing carbon emissions of the transport sector shall be discussed in this chapter. An initial evaluation of these alternatives will be done, and their advantages and disadvantages would be identified. Following that, ASEAN's transport sector and energy sector shall be investigated. Based on these observations, the alternatives that are most suitable for ASEAN countries will be identified. Finally, the primary questions to be answered in this thesis will be formulated. The methodology adopted for initial evaluation of the alternatives is published as an article titled 'Well to wheel analysis of low carbon alternatives for road traffic' [12] in the Energy and Environmental Science journal and was well received by the scientific community.

2.1 Available low carbon alternatives for road transport and their environmental impacts

2.1.1 Description of the available alternatives

Regarding road transport, engineers and policy makers are exploring sustainable alternatives which produce less emissions and use the existing resources at a higher efficiency. Along with a shift towards public transportation, the International Energy Agency [IEA] has proposed the inclusion of alternatives such as electricity, hydrogen and biofuels for mitigating the carbon emissions of the transport sector [13]. An initial assessment of the alternatives mentioned viz. electricity, hydrogen and biofuels is necessary to comprehend the pros and cons of these alternatives. In a journal publication titled 'Well to wheel analysis of low carbon alternatives for road traffic' this initial assessment was done. The primary aim of the work is to compare battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) and bio-ethanol based solutions based on their GHG emissions. The findings of this study would then be applied for the ASEAN region and the questions that are to be answered in this thesis shall be formulated.

2.1.2 Existing methods for evaluation of the alternatives – state of the art

Life cycle assessment (LCA) is a technique that evaluates the environmental aspects of a product, throughout its lifecycle, from raw material acquisition, through production, use, end of life treatment and disposal. Well to wheel (WTW) analysis is a transport specific application of LCA which is used to compare the environmental performance of different drivetrains and vehicles. The above-mentioned road transport alternatives shall be compared using a WTW analysis. A WTW analysis not only considers the emissions involved with combustion of the fuels, but also considers the emissions associated with its production, transportation and distribution.

Several studies have been done based on WTW analysis for comparing various vehicle–fuel combinations. Sheldon S. Williamson and Ali Emandi compared the WTW efficiencies of fossil fuel based hybrid electric vehicles (HEVs) and FCEVs [14]. The influence of the primary energy supply and range on WTW emissions and efficiency of a BEV and FCEV was compared in the work of Stefano Campanari et al. [15]. C. E. Thomas compared alternative vehicles including partially electrified drivetrains such as HEV fuelled by gasoline, ethanol and hydrogen and fully electric vehicles powered by batteries or hydrogen-fuel cell (FC) combinations through dynamic computer simulations to gauge their societal benefits [16]. U. Eberle et al. compared ICE vehicles, HEVs, compressed natural gas vehicles, BEVs and FCEVs on the basis of their WTW GHG emissions [17]. The potential changes in primary emissions and energy use by replacing the U.S. fleet of conventional on-road vehicles with HEVs and hydrogen-based FCEVs (powered by different sources for hydrogen viz. steam reforming of natural gas, electrolysis powered by wind turbine and gasification of coal) through an LCA was examined by W. G. Colella et al. [18]. The JEC Consortium carried out a study, done jointly by the experts from the JRC (European Union Commission’s Joint Research Centre), EUCAR (the European Council for Automotive research and development) and CONCAWE (European oil company organisation for environment, health and safety) [19]. They analysed in detail the future of automotive fuels and powertrains in the European context through a WTW analysis to evaluate the WTW energy use and GHG emissions for a wide range of potential future fuel and powertrain options.

2.1.3 Methodology adopted for evaluation of the alternatives

In this work, the GHG emissions of the three low carbon alternatives proposed by IEA shall be compared based using a WTW analysis. The comparison will be made on ‘*per km driven*’ by a midsize passenger car. In addition to the work mentioned above, the impact that the energy mix of electricity production of a country has on the GHG emissions of a BEV shall be studied. Though BEVs do not produce tailpipe emission, their WTW emissions depend on the primary source of energy used for electricity production. By taking the example of the following countries, the impact energy mix of electricity production has on the emissions of a BEV can be quantified.

1) Germany (fossil fuel dominant)
2) France (nuclear dominant)
3) Sweden (renewable dominant with negligible fossil resources)
4) Austria (renewable dominant with a part of power from fossil resources)

European countries are chosen for this evaluation as the data from the JEC study (which was also done for European countries) [19] could be applied directly. The hydrogen-based solution will be evaluated through a FCEV that uses polymer electrolyte membrane (PEM) fuel cell. Globally, hydrogen is primarily produced by steam reformation of natural gas (NG) [20]. Hence, NG is chosen as the primary source of hydrogen for this study. The option of using compressed natural gas (CNG) directly with FCEV through an onboard reformer is also considered.

The primary biofuel of choice in this study is bio-ethanol as it has a high energy density, is non-toxic and renewable. Globally, it is also the largest produced biofuel [21]. The influence of including bio-ethanol in transport sector shall be analysed through the WTW analysis of ethanol reformate-based FCEVs. These FCEVs can use ethanol at efficiencies higher than ICEs as they are not restricted by Carnot efficiency [22]. In addition to this, the impact of a novel concept, a direct ethanol fuel cell (DEFC), on the overall energy usage and the global GHG emissions, which has not been dealt with before, shall be discussed. The standard sources of ethanol used in this study and their reason of choice are:

1) Corn – The largest source of bio-ethanol production in USA, the world largest producer of bio-ethanol [23]
2) Sugarcane – Brazil, the second largest producer of bio-ethanol use sugarcane for bio-ethanol production [23]
3) Sugar beet – Though wheat remains to be the source of bio-ethanol in Europe [24] (the third largest producer of bio-ethanol [25]), sugar beet is chosen owing to its higher yield [23].

Other non-conventional sources, such as wheat straw and wood waste are considered in this study as well. This is done to assess the WTW emissions of second generation bio-ethanol, that can be derived from waste streams. The different fuel sources considered are summarised in Figure 2.1.

BEV	FCEV	Bio-ethanol
Electricity mix of: • Germany • France • Sweden • Austria	• Natural gas steam reformation • CNG – on board reformer	• Corn • Sugar cane • Sugar beet • Wheat straw • Wood waste

Figure 2.1: Various vehicle fuel combinations considered in this study

The WTW analysis is further split into well to tank (WTT) and tank to wheel (TTW) evaluation. The WTT evaluation deals with the energy needs and emissions associated with bringing the fuel (i.e., electricity, hydrogen or bio-ethanol) into the vehicle while the TTW deals with the emissions and energy needs of the vehicle. The combination of the two will provide the WTW analysis.

2.1.3.1 Tank to wheel evaluation

The energy expended, and the emissions of the vehicles, during its usage on road are to be evaluated in this section. There are standard databases such as GREET, ecoinvent, etc. that are available, which provide these data for emissions and energy needs of a standard BEV and FCEV. However, as these databases do not provide the values for ethanol reformer-based vehicles and DEFC vehicles, it is not possible to use these values. Hence vehicle simulations and standard drive cycles are used to evaluate the energy needs of the vehicles under consideration. The range of the vehicle is taken to be 200 km and the drive cycle considered is the New European Driving Cycle (NEDC). The speed profile of NEDC, which typically lasts for 1180s covering approximately 11 kms, is shown in Figure 2.2. The tailpipe GHG emissions of BEVs and FCEVs are zero. Though bio-ethanol based vehicles produce tailpipe emission of GHGs, they are biogenic and hence do not contribute to the global warming effect (further discussed in chapter 4).

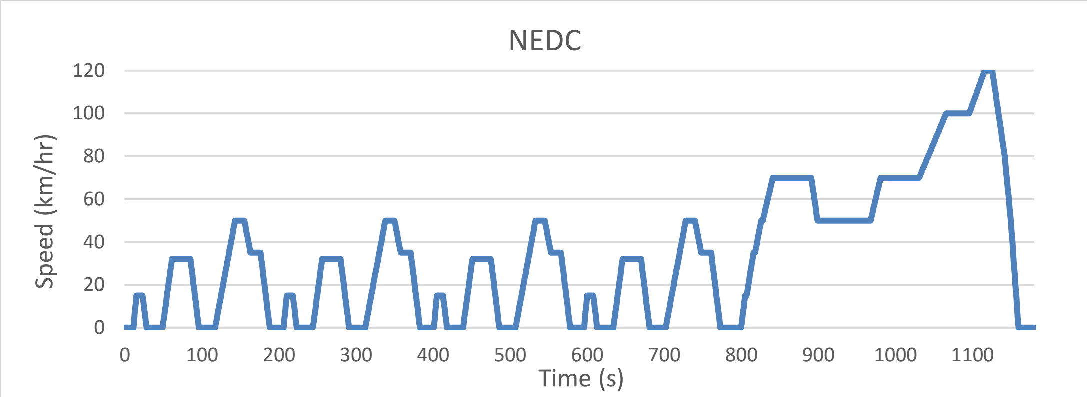

Figure 2.2: The New European Driving Cycle

Li-Ion batteries, the most accepted battery of choice for BEV applications [26], [27] is chosen for this study. Strictly speaking, BEVs do not have a tank and hence they need to be called plug to wheel evaluation. However, the term TTW is maintained for the sake of uniform representation. For the hydrogen based FCEVs, PEM FCs, which have the highest potential for automobile application [15] is considered. For ethanol and CNG based FCEVs, an on-board reformer is included in the vehicle. The schematic representation of the drivetrains is shown in Figure 2.3.

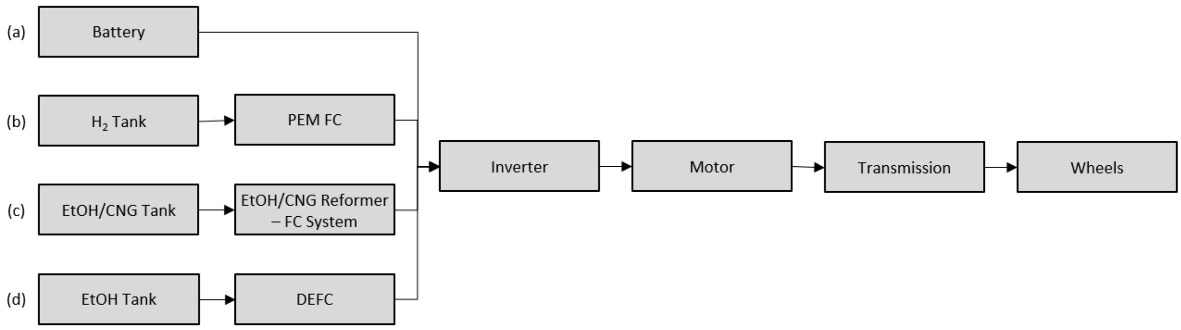

Figure 2.3: Schematic representation of the drivetrain of (a) BEV, (b) H_2-FCEV, (c) Ethanol/CNG reformer based FCEV and (d) DEFC vehicle

The TTW energy demand of a vehicle is the integral of the instantaneous power demand at the tank. The power demand at the tank is evaluated by calculating the power demand at the wheel and dividing it by the efficiency of the respective drivetrain. The efficiency of the drivetrain components considered in this study are given in Table 2.1. The power demand at the wheels is calculated using equations eq 2.1 to eq 2.5 [28].

Component	Efficiency	Source
Battery- Lithium ion	0.95	[29]
Inverter	0.97	[30]
Motor	0.95	[31]
Transmission	0.95	[32]
H2 PEM FC System	0.55	[15]
CNG - Reformer- H2 PEM FC System	0.31	estimated
EtOH - Reformer- H2 PEM FC System	0.41	[33]
DEFC	0.5	estimated

Table 2.1: Efficiency of the drivetrain components

$$P_{accln} = m \cdot v \cdot a \cdot f_{rot} \quad \text{(eq. 2.1)}$$

$$P_{ad} = 0.5 \cdot c_w \cdot A \cdot \rho \cdot v^3 \quad \text{(eq. 2.2)}$$

$$P_{roll} = f \cdot m \cdot g \cdot cos\theta \cdot v \quad \text{(eq. 2.3)}$$

$$P_{inc} = m \cdot g \cdot sin\theta \cdot v \quad \text{(eq. 2.4)}$$

$$P_{total\_wheel} = P_{accln} + P_{ad} + P_{roll} + P_{inc} \quad \text{(eq. 2.5)}$$

$$P_{tank} = \frac{P_{total_{wheel}}}{\eta_{drive\ train}} \quad \text{(eq. 2.6)}$$

$$E_{tank} = \int_{Drive\ cycle} P_{tank} \quad \text{(eq. 2.7)}$$

, where ‘P_{accl}’, ‘P_{ad}’, ‘P_{roll}’, ‘P_{inc}’, ‘P_{total_wheel}’ and ‘P_{tank}’, represent the power required for acceleration, the power required to overcome air drag, the power required to overcome rolling resistance, the power required to climb incline, the total power required at wheels and the power requirement at tank respectively. ‘$\eta_{drive\ train}$’ denotes the efficiency of the drivetrain. The total mass of the vehicle is given by ‘*m*’ and the slope of the road (‘θ’), which is assumed to be zero. The acceleration and velocity of the vehicle are represented by ‘*a*’ and ‘*v*’ respectively. The definition and the value of the other variables used in equations (eq. 2.1) - (eq. 2.4) which are defined by the vehicle being simulated could be found in Table 2.2. This data corresponds to a midsize car.

Variable	Symbol	Units	Value
Air drag coefficient	c_w	(-)	0.31
Coefficient of rolling resistance	f	(-)	0.011
Frontal area	A	m^2	2.2
Rotational inertia coefficient	f_{rot}	(-)	1.1
Mass of kerb vehicle	m	kg	1100
Slope	θ	rad	0
Density of air	ρ	kg/m^3	1.225
Acceleration due to gravity	g	m/s^2	9.81

Table 2.2: Configuration of the simulated vehicle [34]

From equations (eq. 2.1) - (eq. 2.5), it is seen that the energy demand of a vehicle depends on the drive cycle, form of the vehicle and the mass of the vehicle. While the first two factors remain the same for all vehicles under consideration, the mass of the vehicles will vary considerably based on the drivetrain. The mass of the vehicle depends on the specific energy of the storage device used (i.e., battery, hydrogen storage tank, etc.). This is the reason why BEVs in general are heavier than FCEVs and ICE vehicles. For a fair calculation of energy consumption, it is assumed that all the vehicles have the same kerb mass. Then the weight of the drivetrain (and energy storage device) is added to this kerb mass. The kerb mass is taken to be 1100 kg [15], representative of a medium sized passenger car. Regenerative braking is included in the model. Since BEVs have bidirectional energy flow, the effect of regenerative braking is easily evaluated. Whereas for FCEVs, it is estimated that the TTW energy consumption reduces by 9% for an additional mass of battery pack of 15 kgs [15].

Iterative mass estimation: The mass of the energy storage device depends on the energy demand, while the energy demand is also affected by the mass of the vehicle (which includes mass of the storage device Hence, there is need to solve this iteratively to find the suitable mass of the storage system for the specific range, which was done using MATLAB scripts. The specific energy densities of the storage system considered are given in Table 2.3. The range of the vehicle was fixed to be 200 kms.

Component	Specific energy *(MJ/kg)*	Storage tank mass ratio *(kg tank/kg fuel)*
Li-ion battery	0.432	-
Compressed H_2	120	17.4
CNG	48	1.75
Ethanol	26.8	0.10

Table 2.3: Storage device specifications [15]

The TTW efficiency of BEV and FCEV in this study are 83% and 48% which matches that from the ones found in literature [15], [35]. The sizing of the power converters is done based on the peak power demand. The power densities of the PEM FC stack, reformer and DEFC are taken to be 1000 W/kg, 800 W/kg [15] and 500 W/kg respectively.

The TTW energy needs of the various vehicles calculated by the above-mentioned method is tabulated in Table 2.4. These absolute numbers might not be comparable to that from standard databases since they do not include the energy needs of auxiliaries such as lights, air conditioning, etc. However, this is enough for the comparison of the different vehicles under consideration, as the assumption is made uniformly across all the vehicles. Also, the ratios of energy consumption of BEV and FCEV are comparable to the ones found in GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model [36]. The values for petrol and diesel vehicles are taken from the JRC report [19], by normalising the vehicle assumed in this thesis to the one found in JRC study, through the energy consumptions evaluated.

Vehicle type	TTW Energy consumption *(MJ/100km)*
BEV	44.4
H2-FCEV	71.2
CNG-FCEV	131.7
EtOH-FCEV	99.2
EtOH-DEFC	78.9
Petrol	164.2
Diesel	125.6

Table 2.4: Tank to wheel consumption of the energy needs

2.1.3.2 Well to tank evaluation

As mentioned previously, the WTT evaluation deals with the efficiency and emissions involved in production, transmission, transportation and distribution of fuels (i.e., electricity, hydrogen, bio-ethanol, etc.). The values used in the evaluation are taken from the work done by joint research centre (JRC) for the JEC (JRC, EUCAR, CONCAWE consortium) WTW analysis which is published as WTT report version 4.1 [37] [38]. This is a comprehensive study carried out by JEC which includes the process of producing, transporting, manufacturing and distributing several fuels, that are suitable for powertrains of road transport. The report and the supplementary material of this study can be found here [39]. GHG emissions is the focus of their study. Production and conditioning of primary energy at the source, transformation of primary energy at the source, transportation of the fuel, transformation at the site and conditioning and distribution of the fuel are the major steps involved in the WTT evaluation. The emissions, energy requirements and efficiencies of each of the above-mentioned steps have been calculated per 1 MJ of final fuel.

The fuels that are relevant to the evaluation are, electricity, hydrogen, CNG and bio-ethanol. There are multiple pathways for producing these fuels. For instance, electricity from NG can be produced by conventional or combined cycle gas turbine (CCGT) power plant that may or may not use carbon capture and storage. The emissions of these pathways would vary largely. However, this analysis restricts itself only to the most prominent pathways. Each pathway is referred to by a special code in the WTT report. For the ease of cross reference with the report, the code of the pathway (used in the report) is mentioned. Following is the detailed description of the individual fuels.

Electricity: For evaluating the emissions of electricity production in each country, the following technique is applied. The primary energy source of electricity generation for each country is identified from 'The World Bank – World Development Indicator' data source and plotted in Figure 2.4 [40]. Then for each energy source, a pathway for electricity production is chosen from the JRC report [38]. The case of wind turbine is assumed for all the renewables. The most relevant pathways of electricity generation are shown in Table 2.5. Using emission factor of individual technology and the energy source of electricity generation, the emissions of electricity generation of the energy mixes considered is evaluated. The emissions so evaluated are tabulated in Table 2.6.

Source	Type of Power plant	WTT Code	WTT Emission Factors *(g CO_2 eq/ MJ elec.)*
Coal	Conventional coal power plant	KOEL1	292.4
Oil	Heavy fuel oil in conventional power plant	FOEL1	237.8
Natural Gas	CCGT power plant, 4000 km NG pipeline	GPEL1b	132.4
Nuclear	Fission reactor	NUEL	5
Biomass/ Waste	Biogas ex municipal waste, local	OWEL1a	13.6
Renewable	Wind Turbines	WDEL	0

Table 2.5: Well to tank emissions of electricity generated from different energy sources

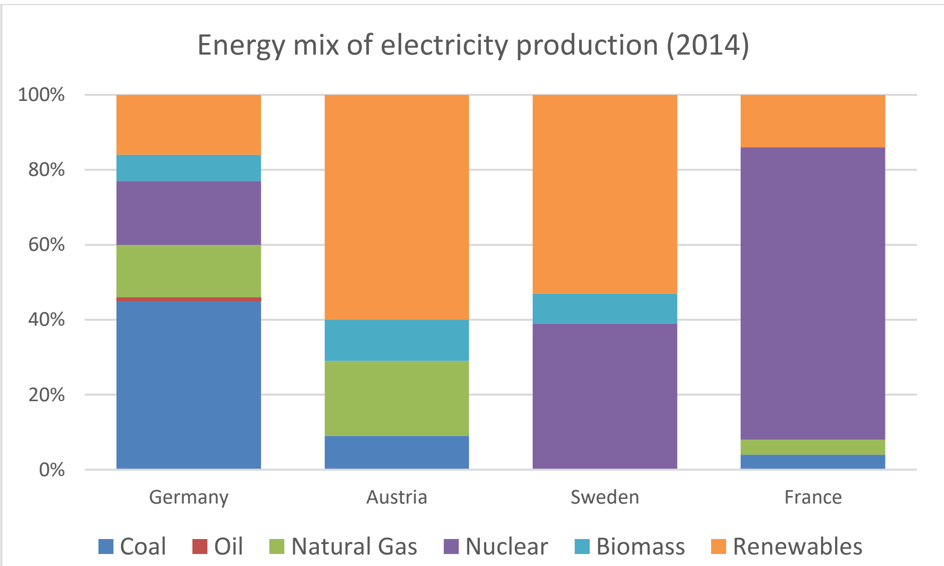

Figure 2.4: Energy mix of electricity production for the various countries considered for the year 2014

Hydrogen: As mentioned before, the major source of hydrogen considered is NG. Hydrogen is produced from NG through steam reforming. There are two configurations that are considered

1) Transport of NG through pipelines followed by on site (OS) reforming
2) Reforming NG centrally and transporting the hydrogen

Both the pathways are considered in the study. The emissions of the same along with their WTT codes are tabulated in Table 2.6.

CNG: Pipelines are used for transportation of CNG. The emissions of the same are shown in Table 2.6.

Bio-ethanol: The major sources of bio-ethanol considered in this study are corn, sugar cane, sugar beet, wheat straw and wood waste. Fermentation is the process that is used for ethanol production. There are multiple pathways for each process itself. The ones that are considered are tabulated in the Table 2.6 (along with their WTT code).

Source/Pathway	Fuel ref. code	WTT Code	WTT-GHG emissions *(g CO_2 eq/MJ fuel)*
Electricity			
Germany E mix	EGE	Refer Table 2.5	156.9
Austria E mix	EAU		49.4
Sweden E mix	ESW		8.8
France E mix	EFR		21.9
Hydrogen			
NG - OS reforming	HNO	GPCH1b	117.7
NG - Central reforming	HNC	GPCH2b	104.4
Natural Gas			
Pipeline	NGP		16.1
Bio-ethanol			
Sugar beet	BSB	SBET1c	17.8
Corn	BCO	CRETus	68.9
Sugarcane	BSC	SCET1	24.8
Wheat Straw	BWS	STET1	9.2
Wood Waste	BWW	STET1	19.5

Table 2.6: Well to tank emissions for different fuels considered in this study

2.1.4 Well to wheel emissions of the alternatives - Results

The well to wheel emissions are a combination of the WTT and TTW evaluations made in the previous sections. The WTW emissions of the various combinations considered in this study are tabulated in Table 2.7. The emissions of the conventional vehicles in Table 2.7 is taken directly from the report [38]. Since the vehicle configurations might be different, the emission values are normalised by the energy consumption of the BEV found in the report.

2.1.4.1 Observations

Battery electric vehicle: The emissions of BEVs are lower than those of conventional vehicles. However, their WTW GHG emissions between different countries vary largely (by a factor of 20). The emissions of a BEV depend largely on the energy mix of electricity production. Higher the dependence on fossil fuels, higher the GHG emissions. In the case of Germany whose electricity production depends 60%

on fossil fuels, the GHG emissions of BEV are close to 61% of that of a diesel car. Hence BEVs might not offer a highly sustainable solution for grid mixes that heavily depend on fossil fuels, especially coal. On the other hand, BEVs driven by a nuclear dominated electricity mix (France) have a very low carbon footprint of 9.7 g CO_2 eq/km. The main reason for this is that most of the carbon emissions involved with nuclear electricity arises from fossil fuel energy used in mining, transport, nuclear fuel enrichment and power plant maintenance [37]. Though nuclear electricity is very less carbon intensive, there are other issues such as safety and nuclear waste disposal associated with it. The percentage of global electricity supplied by nuclear electricity has been decreasing consistently [40], and a few countries have already started to phase it out [41], [42]. If a BEV is driven by carbon free, renewable energy sources like that of Austria and Sweden, they offer very low carbon footprints of 21.9 and 3.5 g CO_2 eq/km respectively. The lower number of for BEVs in Sweden is because it is completely independent of fossil fuels.

Fuel-Vehicle Combination	Emissions *(g CO_2 eq/km)* WTW	TTW
Battery electric vehicle		
EGE-BEV	69.7	0.0
EAU-BEV	21.9	0.0
ESW-BEV	3.5	0.0
EFR-BEV	9.7	0.0
Hydrogen fuel cell vehicle		
HNO-FCEV	83.7	0.0
HNC-FCEV	74.2	0.0
Natural gas fuel cell vehicle		
NGP-FCEV	88.5	67.3
Ethanol reformate fuel cell vehicle		
BSB-FCEV	17.6	0.0
BCO-FCEV	68.2	0.0
BSC-FCEV	24.6	0.0
BWS-FCEV	9.1	0.0
BWW-FCEV	19.3	0.0
Direct ethanol fuel cell vehicle		
BSB-DEFC	14.1	0.0
BCO-DEFC	54.4	0.0
BSC-DEFC	19.6	0.0
BWS-DEFC	7.3	0.0
BWW-DEFC	15.4	0.0
Conventional vehicles		
Petrol-ICE vehicle	144.0	121.0
Diesel-ICE vehicle	113.0	93.0

Table 2.7: WTW and TTW emissions of the various fuel vehicle combinations

A few aspects that work against the immediate implementation of BEV are, it's limited range and longer recharge periods. It also requires implementation of non-residential charging stations on a large scale for its proper implementation [43] which involves high capital cost.

Hydrogen: The WTW GHG emissions of hydrogen-based FCEVs are better than that of fossil fuels. However, they perform worse than BEVs even if the electricity is derived from a fossil fuel-based electricity mix. Though the hydrogen-based fuel cell does not produce any tailpipe GHG emission, the production of hydrogen itself (which is dependent on NG) is carbon intensive (104.4-117.7 g CO_2 eq/MJ fuel). The lower carbon emissions of central reforming suggest that it is more efficient than the onsite reformation process. If NG is used to produce electricity in a combined cycle power plant and used to power a BEV, then its carbon footprint would be 58.8 g CO_2 eq/km. This is lower than if NG is used to produce hydrogen and subsequently used in an FCEV.

In addition to having a lower carbon footprint, the alternatives need to offer a sustainable solution, for which they need to be able to include renewable energy sources. Using renewable electricity to produce hydrogen through electrolysis of water could offer a promising solution as this would produce no operative GHG emissions. However, electrolysis is a relatively inefficient energy conversion process. Using renewable electricity directly in BEV requires 48.3 MJ per 100 km as opposed to 141.7 MJ per 100 km if driven using hydrogen derived from renewable electricity. BEVs can utilise renewable electricity at higher efficiency. Hence hydrogen FCEVs do not offer a sustainable solution. However, FCEVs do offer the advantages of longer range per recharge and smaller refuelling/recharge time in comparison with a BEV. Hydrogen can be more advantageous in larger vehicle segments due to this reason. However, the implementation of hydrogen-based FCEV system requires the development of infrastructures for distribution and refuelling which deters its immediate implementation

CNG: NG is the main source for hydrogen production. Instead of reforming it outside the vehicle, it could be reformed onboard. The WTW GHG emissions of such a system is in similar range of a hydrogen FCEV. The main advantage this configuration offers over hydrogen FCEV is the relative ease of storage and distribution of CNG over hydrogen. However, on board reformation of NG is not an easy process. Also, complete dependence on fossil fuels makes it a less sustainable solution.

Bio-ethanol:

<u>Ethanol reformate fuel cell:</u> The GHG emissions of bio-ethanol when used in ethanol reformate FCEVs are lower than that of conventional vehicles. However, they vary largely based on the source of ethanol. FCEV driven by bio-ethanol derived from corn and wheat straw has the highest (68.23 g CO_2 eq/km) and the lowest (9.11 g CO_2 eq/km) carbon footprint respectively. Though the use of bio-ethanol produces tail pipe carbon emissions, this CO_2 was originally absorbed by the plants from the atmosphere during their growth phase (explained in greater depth in Chapter 4). This is the reason for their lower carbon footprint. The GHG emissions given in Table 2.7 are the ones associated to the energy and material inputs involved with the growth, transportation and transformation of biomass [22]. The GHG emission of these vehicles lies in the range of 16-43% (barring corn) of a BEV driven by the energy mix of Germany (which is fossil fuel dominated). However, they perform worse than the BEVs if operated by nuclear or renewable electricity. Hence bio-ethanol is more suited for countries that have high fossil fuel penetration.

Bio-fuels in general suffer from the issue of land usage. They compete with food crops for agricultural land [44]. Producing bio-ethanol from residues such as wood waste and straw (agricultural residues) would help counter these issues. As seen from Table 2.7, the GHG emissions of an ethanol FCEV that uses wood waste and wheat straw are very low. Their emission levels are comparable to that of BEVs driven by renewable and nuclear fuel mixes. The main reason for the same is that the energy associated with the development of the crop is associated with the crop and not the waste (i.e., straw). Bio-ethanol from waste also offers the advantage that they can avoid organic wastes from entering the landfills, which may produce additional GHG emissions. Hence bio-ethanol, especially when produced from agricultural residues could offer low GHG emission solutions. For countries with high fossil fuel penetration, bio-ethanol could perform better than BEVs in terms of emissions.

Direct ethanol FCEV: The benefits of bio-ethanol could further be enhanced if it is utilised in DEFCs. The higher efficiency and compact design of DEFC can utilise bio-ethanol at better rates. DEFC can potentially have energy and power densities higher than ethanol reformer fuel cells. They also have a simpler construction involving lesser parts.

Bio-ethanol also offers advantages other than low global GHG emissions. The have good energy density and are of renewable nature. They have the advantage of immediate implementation as a mix with gasoline. They can be readily used at lower blends (such as 5%) and at higher rations with slight modification to the engines [27]. They do not require development of new infrastructure such as charging stations or storage tanks like that of BEV or hydrogen FCEVs.

2.1.4.2 Key inferences drawn from the initial results

- Electricity, hydrogen and bio-ethanol based vehicles can have GHG emissions lower than conventional vehicles.
- Hydrogen is the least sustainable option among the alternatives.
- Emission saving potential of BEVs depend largely on the electricity generation mix.
- BEVs perform better if the grid is nuclear/renewable energy dominated.
- Bio-ethanol performance is comparable to that of BEVs.
- Bio-ethanol is better than BEVs in the countries that have a fossil fuel dominated electricity mix.
- Bio-ethanol if derived from bio-residues (agricultural and forest residues) could provide a low GHG, sustainable solution.

2.2 Brief overview of ASEAN's energy, emission and transport scenario

Gaining the background knowledge of ASEAN's electricity and transport sector is important to apply the findings of the initial assessment here.

2.2.1 Emissions from fuel combustion

As discussed before, the economic growth is always coupled with the growth in energy consumption. Figure 2.5 gives the CO_2 emissions arising from fuel combustion in ASEAN. Indonesia, Malaysia and Thailand are the major contributors. It is observed that the total emissions have increased from 356 million tonnes in 1990 to 1265 million tonnes in 2015, by a factor of 3.6. In the same period the global CO_2 emissions has increased only by a factor of 1.6. The global share of ASEAN in CO_2 emissions from combustion was only 1.7% in 1990. It has increased to 3.9% by 2015 and is expected to increase further. Apart from the fact that there is a strong economic growth, high dependence on fossil fuels and lesser penetration of renewable energy has caused the growth in emissions.

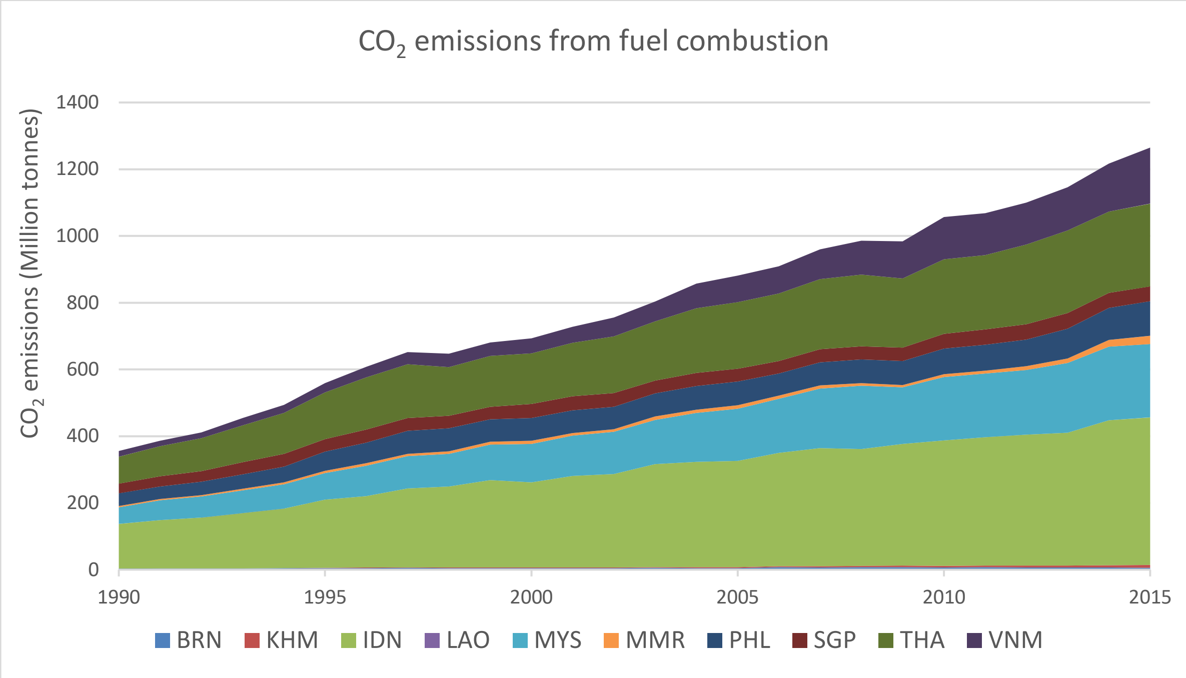

Figure 2.5: CO_2 emissions caused by combustion of fuel in ASEAN nations between 1990 and 2015

As seen from Figure 2.6, the two major contributors of CO_2 emissions in ASEAN are electricity generation and transport. Both the sectors are discussed individually below.

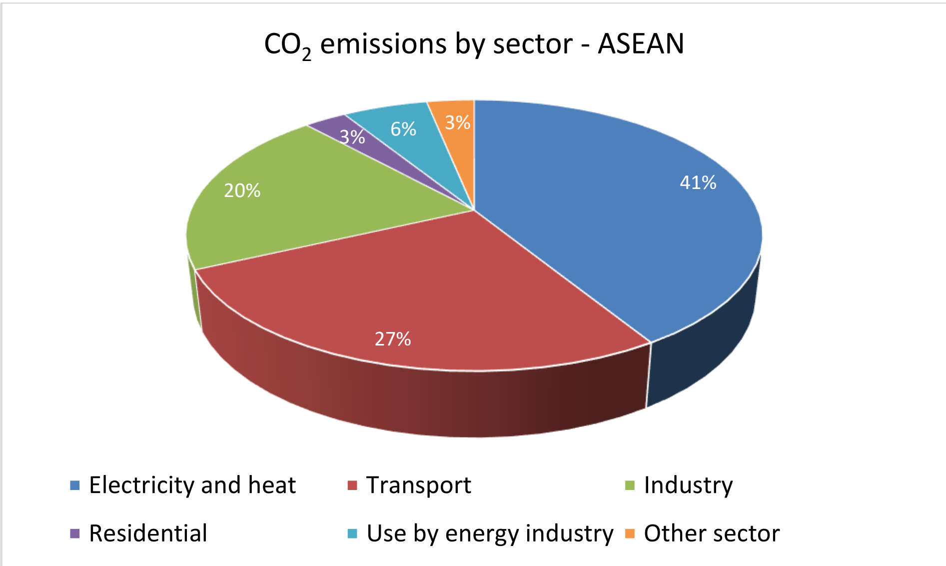

Figure 2.6: Contribution of different sectors to CO_2 emissions caused by combustion of fuel in ASEAN

2.2.2 Electricity production sector

Figure 2.7 shows the total amount of electricity generated and the energy mix of electricity generation in ASEAN. The electricity generation increased by 5.7 times from 155 TWh in 1990 to 886 TWh in 2015. A vast majority of the electricity comes from fossil fuels. Since 1990, the contribution from fossil fuels has been hovering in the range of 80-85%. A lot of oil-based power plants have been replaced by NG power plants. NG is the main source of electricity and contributes to 43% of the total production. Nevertheless, electricity generation from coal is catching up quickly, especially in the past decade.

There is a steep increase in power generation from coal (from 27.2% in 2010 to 36.4% in 2015) and it is expected to grow further in the near future [11]. This is a worrisome trend with respect to emission of GHGs. Though the amount of hydro electricity produced increased from 28 TWh in 1990 to 118 TWh is 2015, its share in total electricity production has decreased from 18% to 13%, courtesy of the increase in electricity generated from the fossil fuels.

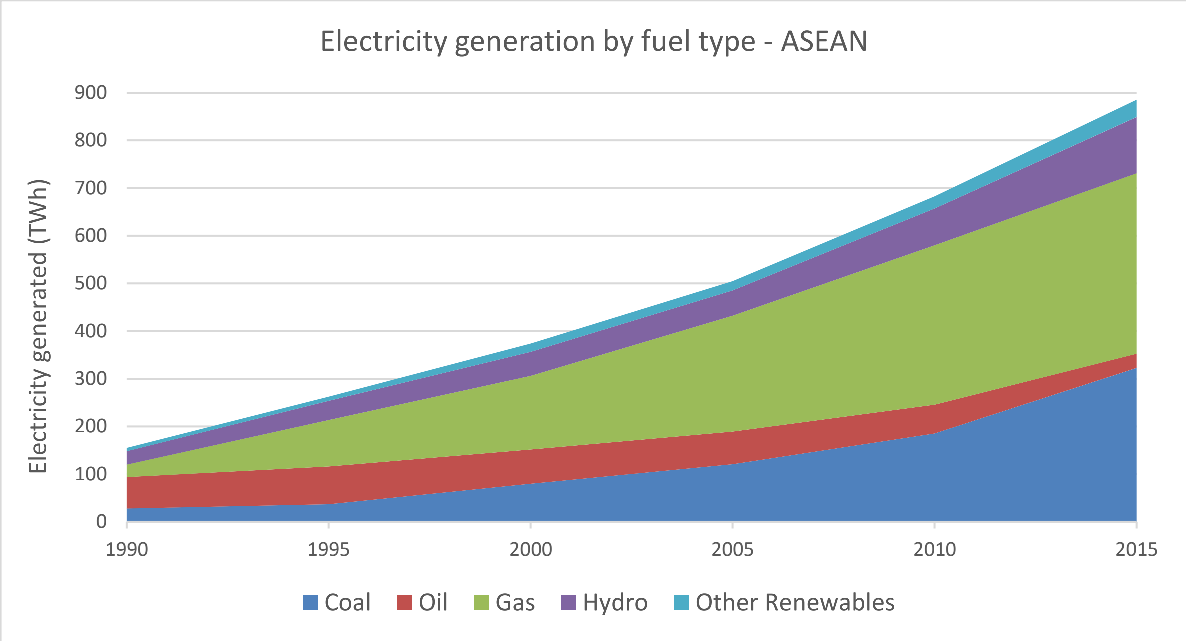

Figure 2.7: Electricity generation by fuel type in ASEAN between 1990 and 2015

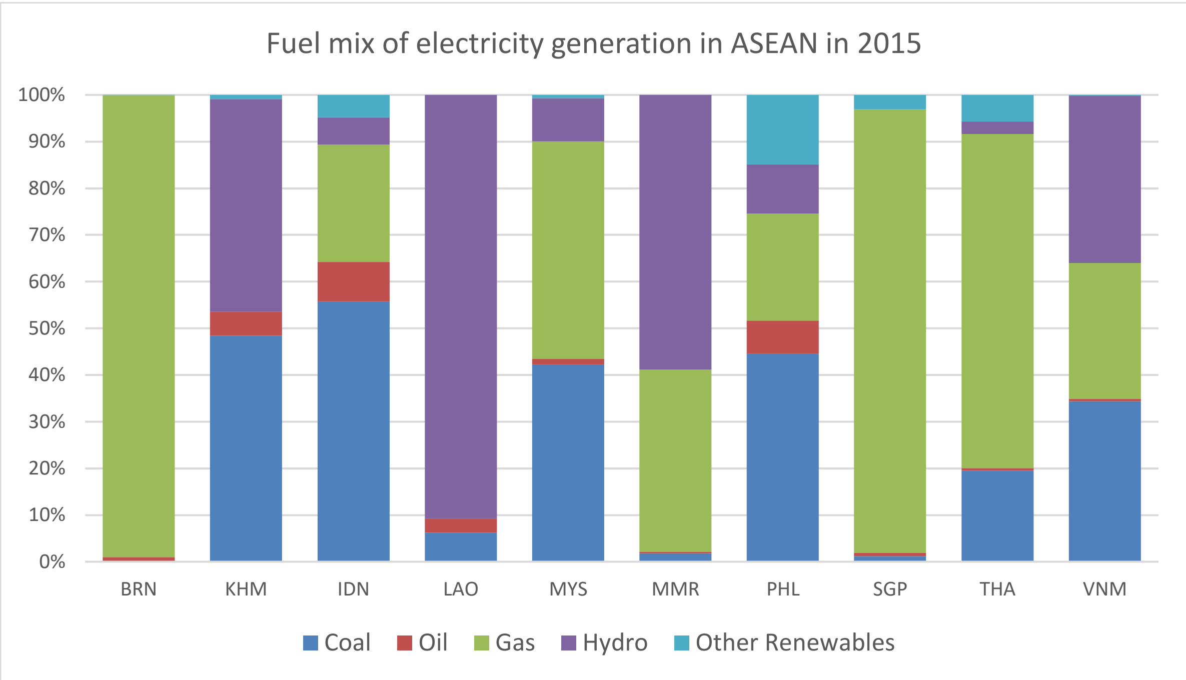

Figure 2.8: Fuel mix of electricity generation across different ASEAN countries in 2015

The amount of electricity produced in each country and the energy mix used for electricity generation varies a lot from one country to another. The energy mix of electricity generation for each country is shown in Figure 2.8. Cambodia, Indonesia, Philippines and Vietnam are dominated by coal whereas, Brunei, Malaysia, Singapore and Thailand are dominated by NG. Laos and Myanmar receive most of their energy from hydro powerplants.

2.2.3 Transport sector

Transport is one of the fast-growing sectors in ASEAN. Rapid economic growth is always associated to a growth in the transport sector. Figure 2.9 gives the historic data on petrol and diesel consumption in ASEAN. The total fuel consumption grew by about 3 times during this period.

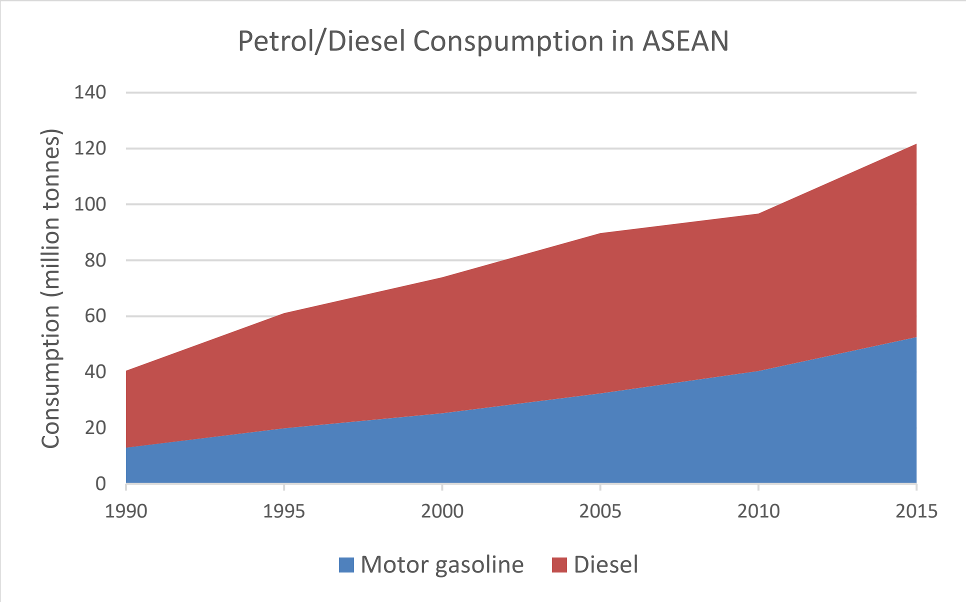

Figure 2.9: Petrol/Diesel consumption in ASEAN nations

Regarding CO_2 emissions, transport sector contributes to 27% of the emissions from fuel combustion as opposed to the global range of 24%. Another interesting trend observed in ASEAN is that, 92% of the transport emissions comes from the road sector. Globally this number is 75%. This suggests that the contribution from other sectors such as aviation and shipping is rather low in ASEAN. Thus, the road transport sector in ASEAN is identified as one of the important sectors that has huge potential for reducing the carbon footprint of these nations.

2.3 Road transport alternatives suitable for ASEAN

The focus of this thesis is primarily on the transport sector. The most suitable alternative for road transport decarbonisation in ASEAN needs to be identified. As seen in section 2.1, the emission mitigation potential of BEVs largely depend on the energy mix for electricity generation. BEVs are not the most sustainable option for a fossil fuel-based grid mix. It was seen in section 2.2.2 that ASEAN is largely dependent on fossil fuels, with no nuclear electricity and small amounts of renewables. It is also expected that the dependency on fossil fuels for electricity production is going to increase. Hence, BEVs might not be the most sustainable option for ASEAN. It is also inferred in section 2.1 that hydrogen does not offer a long-term sustainable solution. Hence, it is left out of the scope of the evaluation. On the other hand, it is seen that bio-ethanol, especially when derived from agricultural residues, might be able to offer a sustainable and a low carbon alternative.

2.3.1 Agricultural residues and biofuel – the most relevant alternative

Agriculture plays a major role in the economies of ASEAN countries. They produce large quantities of crops both for domestic consumption and export. The tropical conditions of ASEAN nations make them conducive for the cultivation of crops such as rice and sugarcane. They also produce a variety of other agricultural products such as palm, wheat, corn, coconut, cassava, groundnut, etc. Figure 2.10 gives the percentage of the agricultural lands for the different ASEAN nations. The total land area under cultivation has been steadily increasing in ASEAN nations. The land area under cultivation grew by 22% from, 1.08 million sq. km in 1990 to 1.32million sq. km in 2015 [10]. The original share of agricultural land in total land area in ASEAN was 24.8% in 1990, which grew to 30.4% in 2015. The share of agricultural land of ASEAN on a global level is only 2.7%. However, ASEAN produces 28% of the global rice, 10% of the global sugarcane and 87% of global oil palm [45]. They have achieved great progress in terms of achieving food security in the recent past [46]. The net agricultural production across ASEAN is expected to grow further [46]. The forests in ASEAN are also a major source of timber and other forest products [47].

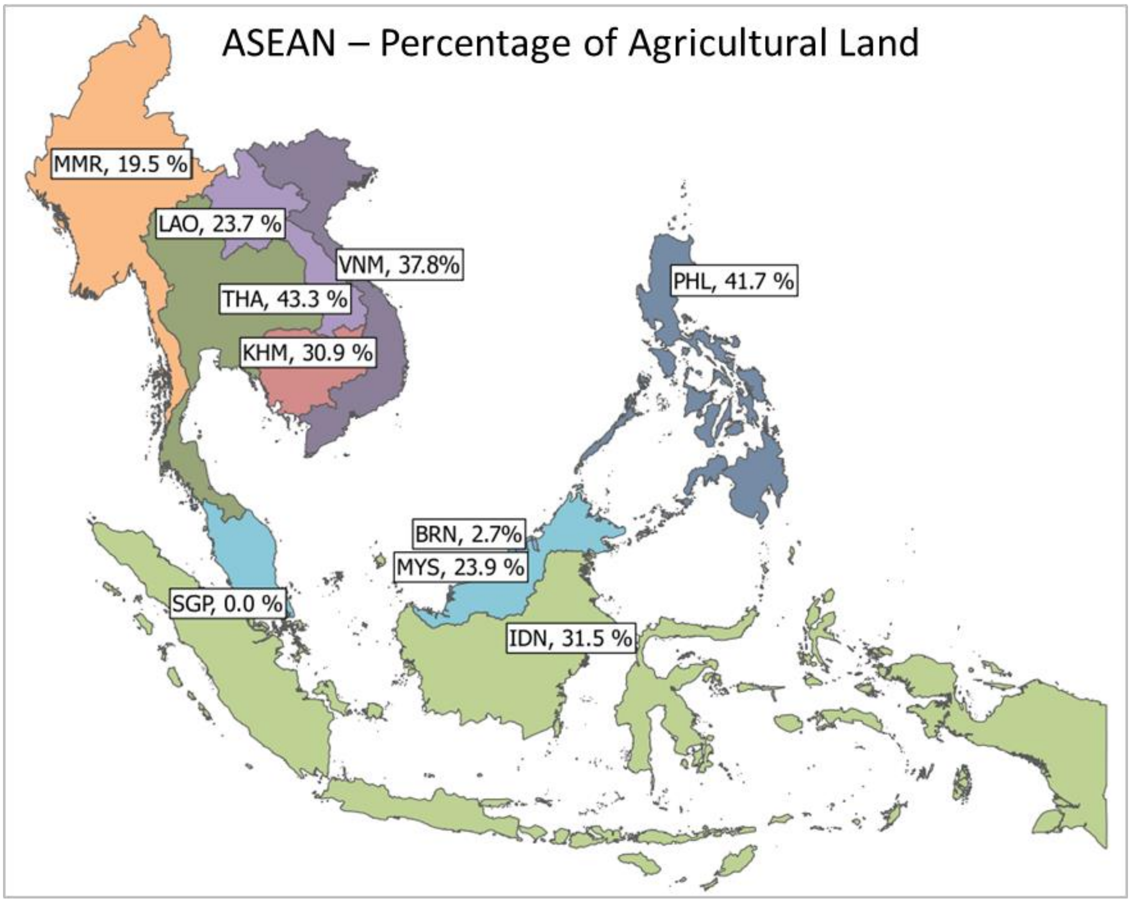

Figure 2.10: Percentage of land under agriculture in ASEAN nations

Agriculture and forestry activities are accompanied by the production of large quantities of biomass residues. Some predictions estimate that 200 – 230 million tonnes per year of residues is available from sugarcane, rice and palm oil alone, in this region [48]. If they are not utilised or treated properly, they would enter landfills. The anaerobic decay of organic matter in the landfills produces methane, which has a global warming potential of 25 times that of CO_2. Hence landfills become net emitters of

GHGs [49]. On the other hand, these biomass residues could be used for energy recovery. By recovering energy from biomass residues and using it to replace the energy derived from fossil fuels, the dual crisis of climate change and waste pileup can be tackled. Thus, it is interesting to analyse if it possible to use the energy derived from biomass residues in ASEAN's transport sector and to estimate the potential emission savings it could offer. This would be the focus of the thesis. The thesis question and its sub parts are discussed in the next section.

2.3.2 Relevant research questions

The primary research question that is to be answered in this thesis is "What is the emission mitigation potential of the use of bio-energy, derived from biomass residues, in the transport sector of ASEAN?". This primary question is broken down into smaller sub sections as described below.

1) *Estimation of the emission levels and energy needs of the existing road transport sector in ASEAN* – The main aim here is to evaluate the existing emissions from road transport in the 10 ASEAN countries, classified by vehicle type, vehicle class and fuel type. This enables the evaluation of the amount of emission that can be mitigated through the inclusion of energy derived from biomass residues in ASEAN's road transport sector.
2) *Quantification of the biomass residues and bio-energy available in ASEAN* – For evaluating how much bio-energy can be produced in ASEAN (that can be used to decarbonise transport sector), the biomass residues availability in ASEAN needs to be quantified.
3) *Evaluation of the environmental performance of energy recovery from biomass residues* – the various pathways through which energy can be derived from biomass residues for its use in the road transport sector shall be discussed. This depends mainly on the type of residues available. The emission of energy recovery of these pathways needs to be estimated as well. The total quantity of bio-energy that can be produced from the available biomass has to be computed.
4) *Estimation of the emission reduction potential at a national level* – The results from the previous three questions must be combined to assess the overall emission reduction potential of bio-energy use in transport sector for each country, for different levels of bio-energy penetration.

The term emissions shall encompass greenhouse gases (CO_2, CH_2, N_2O, etc.), acidic gases (SO_2, NO_X, NH_3, etc.) and direct PM 2.5 emissions. Though all the three emissions are quantified at each stage, the primary focus and discussion is restricted to GHGs only to make the discussion and argumentation focussed and impactful. There is also another reason for this approach. For emission evaluation, emission inventories of various processes ranging across different domains such as electricity production, transportation, biomass densification, bio-fuel production, etc. is needed. The emission inventory also needs to be developed for 10 different countries. Hence the inventory must be chosen from different databases. Since the GHG emissions primarily depend on the carbon content in the fuel, the variation in its values across different emission inventory databases is minimal. However, the same is not the case with emission of other pollutants such as SO_2 or NO_X as they are process dependant. Also, to make the results reliable for pollutants, the emission inventory must be chosen from a single source. Unfortunately, this not possible as study is carried out for 10 nations in various domains. Hence though the emission of acidic gases and PM 2.5 is evaluated, the discussion and argumentation is restricted to GHGs only.

2.3.3 Thesis Structure

Road transport decarbonisation – identification of alternatives relevant for ASEAN (Chapter 2): In the introduction, the issues associated with climate change and CO_2 emissions are discussed. The major causes of climate change are mentioned as well. In the motivation chapter the transport sectors contribution to the GHG emissions is further investigated. The alternatives available for decarbonising road transport are enlisted and a preliminary well to wheel analysis is done to evaluate the alternatives available. A brief analysis of ASEANs energy and transport sector is done and the alternatives most suitable for ASEAN are identified. This chapter also identified the pertinent questions that are to be answered in this Thesis. The thesis is split into further chapters as discussed below to answer the formulated thesis questions.

Vehicle and transport emission inventory for ASEAN (Chapter 3): In order to evaluate the emission mitigation potential of the use of alternatives in road transport, the baseline emissions and energy needs of existing transport needs to be quantified. The main aim of this chapter is to compute this. A database on the vehicle fleet in each ASEAN nation will be created. The vehicle fleet will be further classified by vehicle type, vehicle class, fuel type, etc. Using standardised vehicle emissions/energy consumption models and statistical data on vehicle average speeds and annual distance driven, the emission and energy needs of vehicles at a national level will be evaluated in this chapter. The main output of this chapter is the energy consumption and emission of road transport vehicles for all the ASEAN nations split across vehicle types and classes.

Bio-energy Availability in ASEAN (Chapter 4): In this chapter, the total biomass residues that are available in ASEAN, that can be used for energy purposes shall be estimated. The potential location of these residues shall be identified and mapped based on the land use data. The output of this study is a map showing the location and total quantity of biomass residues available in the 10 ASEAN countries. In addition to that the energy products pertinent for use in transport sector that can be derived from biomass residues shall be identified. The relevant pathways through which they can be derived shall be discussed as well.

Emission saving potential of bio-energy use in ASEAN's transport (Chapter 5): In this chapter, the emission mitigation that the use of energy derived from biomass residues in ASEAN's transport sector shall be evaluated. Firstly, the emissions of different pathways of energy recovery shall be quantified. As biomass is associated with low volumetric energy density and large collection area, the impact of densification processes and centralisation/decentralisation of power plants on emissions and energy recovery shall be analysed in this chapter. Secondly, the bio-energy demand of an alternate vehicle fleet and the potential supply scenario will be identified as well. Finally, the total emission mitigation potential at national level will be evaluated. All the thesis questions framed in Chapter 2 will be answered in this chapter.

Discussion and Outlook (Chapter 6):

In this chapter, a discussion of all the results produced thus far will be made. The outlook section will address two items. Firstly, it will mention the limitations of this study and mention the steps to be taken to address them in the future. Secondly, it will enlist the possible research directions this research could be further led into.

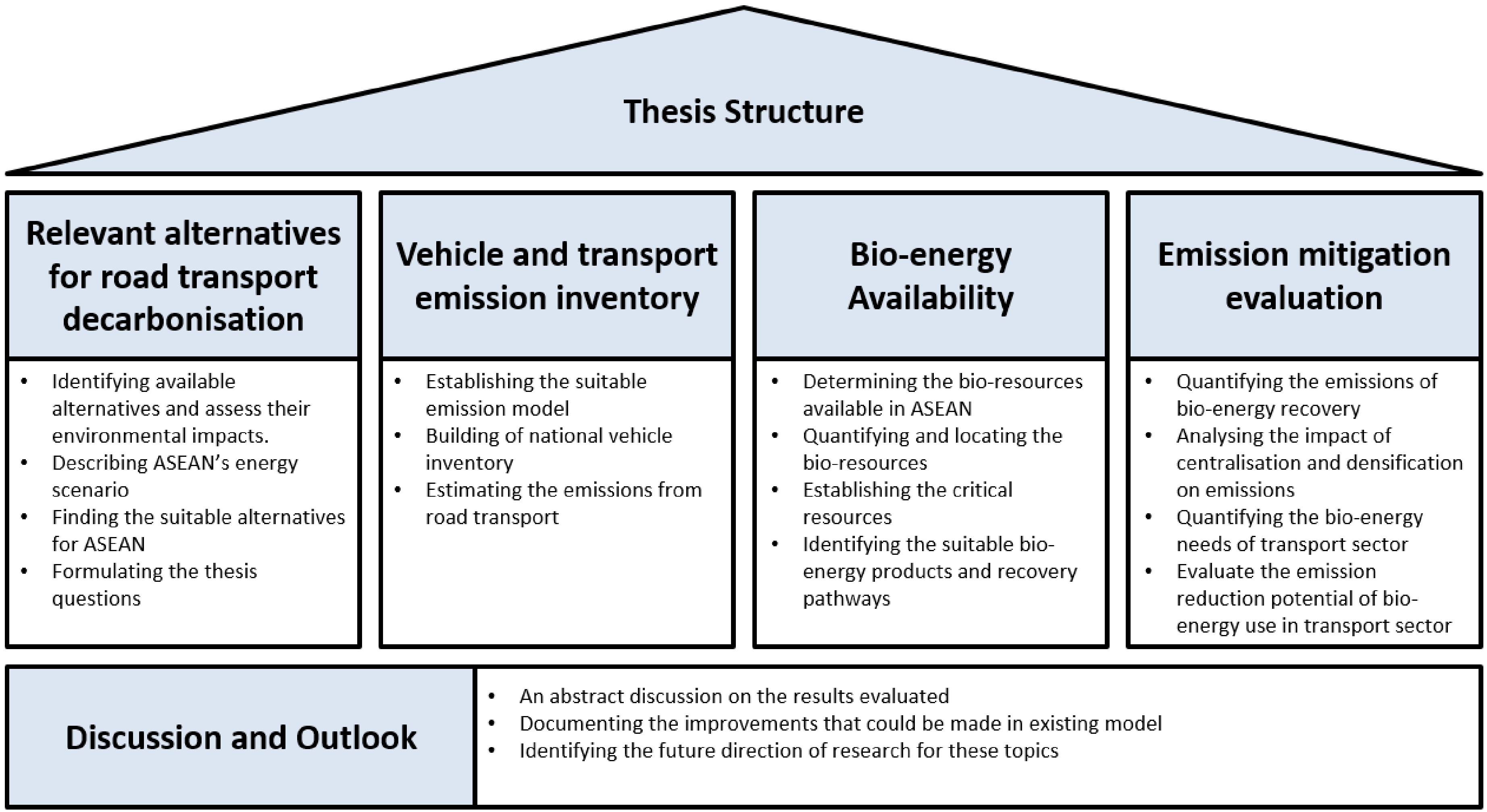

Figure 2.11: A pictorial representation of the Thesis Structure

3 Vehicle and transport emission inventory for ASEAN

In this chapter, the emissions of the existing road transport vehicles in each ASEAN country is evaluated. The main objective of this thesis is to evaluate the emission saving potential of use of bio-energy (i.e., bio-ethanol or bio-electricity) derived from agricultural residues in road transport. For assessing this, the baseline emissions of the existing road transport in ASEAN needs to be established and their energy needs must be quantified. In this chapter, the aggregated emissions at a national level, on an annual basis split across different vehicle and fuel types is estimated.

3.1 State of the art studies on ASEAN's transport emissions evaluation

As seen in Chapter 2, the national statistics on CO_2 emissions from different sectors, including that of transport is already provided by International Energy Agency (IEA) [4]. However, they provide only national aggregates and do not show a split up amongst the vehicle or fuel types. To enable the evaluation of the ideal way to replace the fossil fuel using bio-energy from bio-wastes in ASEAN, the emissions (of all GHGs and pollutants) and energy needs at a finer resolution, e.g., by vehicle type, fuel type, etc. needs to be determined. They also evaluate only the CO_2 emissions and do not include other greenhouse gases (GHGs) or pollutants. Additionally, though this thesis is primarily focussed on GHGs, other emissions (acidic gases and PM) are evaluated as well. Hence the data from IEA would not be enough for our work.

Clean Air Asia (CAA) is an international non-governmental organisation, whose aim is to make the Asian cities cleaner, by suggesting policies and programs that cover air quality, transport & industrial emissions and energy use [50]. The Institution for Transport Policy Studies along with CAA conducted 'A Study of Long-Term Transport Action Plan for ASEAN'. In this study they evaluated the CO_2 emission from transport sector in ASEAN. Unlike the study by IEA, here the emissions are split by vehicle and fuel types [51]. However, this study falls short in the fact that it is consumption-based model. It uses a single emission factor for all the vehicles, based on fuel consumption (g CO_2/litre petrol or diesel). They also focus more on cities and not on the entire country.

Majority of the vehicles in ASEAN countries are presently being powered by fossil fuels, viz. diesel and petrol. Petrol and Diesel are both derived from crude oil which is extracted from the ground. The chain of processes that they need to go through before being used in vehicles is shown in Figure 3.1.

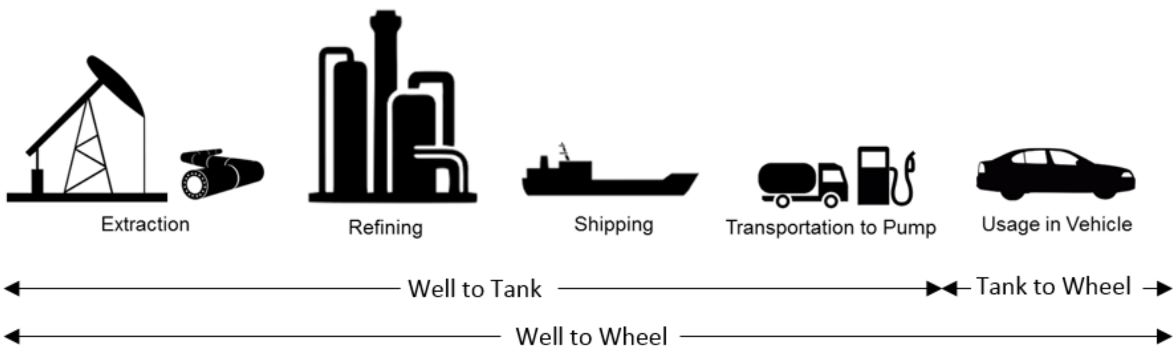

Figure 3.1: Well to wheel pathway of fossil fuel powered transport [52]

3.2 Methodology developed for emission evaluation

An indigenous methodology for evaluating the emissions occurring from road transport in ASEAN, using LCA will be developed. As mentioned previously, LCA addresses the environmental aspects of a product throughout its life cycle, starting from raw material acquisition through production, use, end of life treatment and final disposal [53]. A WTW analysis is an application of LCA, which is used to evaluate the emissions and environmental impact of vehicles or transport systems. WTW analysis is further split into WTT and TTW analysis which is explained in detail in the following sections. The share of vehicles driven by CNG and electricity presently is minimal and hence their contribution to emissions at national level is negligible. Therefore, it is left out of the scope of the evaluation.

3.2.1 Tank to wheel emissions of the transport fleet

This section deals with the emissions produced by the vehicles (on road), during its usage. The focus for this chapter lies with conventional petrol and diesel vehicles. Conventional vehicles extract the chemical energy stored in fossil fuels through combustion in an ICE to produce the required traction energy. Combustion of fossil fuels produce emission of GHGs and pollutants such as CO_2, CH_4, N_2O, particulate matter (PM), NO_x, etc. The amount of emissions produced by a vehicle depends on various factors such as vehicle type, vehicle size, fuel type, emission control standards implemented on the vehicle, driving cycle, etc. To get accurate values of emission of individual vehicles, they need to be tested and measured on a standard vehicle test bed. However, when evaluating emissions at a national level, which would involve various vehicle types and driving conditions, such an approach is impractical. The approach followed in chapter 2 (vehicle simulations) was valid at that level as the primary aim was to compare the emissions and energy needs of alternatives. However, if we need to evaluate real time energy needs and emissions, we need more inputs such as auxiliary loads, drive cycles, emissions of drivetrains for different vehicle types (cars, buses, etc.) which is impossible to develop for 10 different countries.

Hence, for evaluating the emissions on a national scale, the following approach is adopted. First, the average emission levels of a single vehicle type (e.g., medium sized diesel car) on a 'per km' basis is estimated. This factor is then multiplied by the total activity of each vehicle type (i.e., the annual vehicle kilometres travelled (VKT) per vehicle) and number of each vehicle and sum it across the different vehicle types. The total annual emission of a country is given by,

$$E = \sum_{i=1}^{m} e_i \cdot d_i \cdot n_i \cdot 10^{-6} \qquad \text{(eq. 3.1)}$$

Where,

E – Total emissions at national level (tonnes)
i – vehicle type (Car, bus, etc.)
m – number of vehicle types
e – emission factor of each vehicle type (g/km) for example (g CO_2/km, g NO_x/km)
d – annual VKT of each vehicle type (km)
n – vehicle population, i.e., number of each vehicle type (-)

It needs to be noted that the average emission factor (e) of each vehicle type depends further on factors such as average speed, emissions standards, engine size, vehicle size, etc. There are multiple data sources that provide the above data. In section 3.2.1.1, various standard emission inventory databases will be analysed. This is necessary as the nature of each database is different and the one most suitable for the purpose of this thesis needs to be identified. In section 3.2.1.2, the methods through which data acquisition (regarding vehicle population, annual VKT, etc.) is done for building the national emission inventory shall be discussed.

3.2.1.1 Standard vehicle emission inventory databases

There are wide range of databases and vehicle emission models available for procuring the emission inventory/factors of different vehicle types. These can be classified based on their complexity and application. Emission inventory databases (such as ecoinvent, GREET, etc.) gives the emission factor of individual vehicles. Average speed models (such as COPERT, MOBILE, etc.) give emission factors of vehicle as a function of their average travelling speed. More advanced traffic situation models (such as HBEFA, ARTEMIS) give emission factors for specific traffic situations and modal models (such as PHEM, CMEM, MOVES, etc.). They provide emission factors corresponding to specific engines and vehicle operating conditions [54]. The traffic simulation and modal models are more suitable for analysis of specific areas such as cities or towns. Applying them at a national level is a tedious and futile for the purpose of this thesis. Hence, they are left out of the scope of this work. Following section shall focus on the inventory databases and average speed models.

3.2.1.1.1 Ecoinvent

Ecoinvent is the world largest and most accurate life cycle inventory (LCI) database. It is the most comprehensive, transparent and consistent database which is globally well accepted [55]. It contains information on a wide range of processes which include transport and vehicles. Specific to transport, they have emission inventory of car, truck, bus, etc. driven by petrol or diesel on a 'per km' or 'per passenger km' basis. They also include the emissions involved in the manufacturing of the vehicle itself. However, their vehicle emission inventory has a few shortcomings:

1) *Variations in driving speed cannot be accounted for:* Their emission data are based on standard drive cycles. Our aim here is to establish the national emission of 10 different ASEAN nations. The average speed of vehicles in each nation varies a lot. Hence the impact of average driving speeds cannot be accounted for if this emission inventory is used.
2) *Not all vehicle types are included:* Since ecoinvent is not only specific to transport, it does not include all vehicle types. For instance, motorcycles, which are found in abundant numbers in ASEAN, is not a part of ecoinvent.
3) *Variation in vehicle/engine sizes cannot be profoundly found:* For example, emission data for bus is available for one kind of bus only. But at a national level, there are different kinds of buses (e.g., single/double decker transit bus, articulated bus, coach etc.) whose emissions and fuel consumptions differ significantly.

3.2.1.1.2 GREET

The Greenhouse gases, Regulated Emissions and Energy use in Transportation Model (GREET) is an analytical tool developed by the Argonne National Laboratory in the United States and is sponsored by the US Department of Energy's Office of Energy Efficiency and Renewable Energy [56]. It evaluates the emissions and energy use of various vehicle-fuel combination (WTT-TTW combinations). Unlike the ecoinvent, which is a general LCI database, GREET is specific to transport system. Hence, they do have data on different vehicle types on a more detailed level. However, they are more inclined towards GHG emissions only and do not include the variations in the emission caused by different emission standards (e.g., euro standards) and driving profiles (average driving speed).

3.2.1.1.3 COPERT

COPERT is a standard vehicle emission calculator developed by emisia. It is primarily developed for estimating national emission [57]. COPERT contains a huge database on the emissions of a wide variety of vehicle types, namely passenger cars (PCs), light commercial vehicles (LCVs), buses, trucks and motorcycles (MCs) which covers the entire road transport fleet. Each vehicle type is further classified into categories based on its size (for instance a passenger car can be classified into mini, small, medium and large). Furthermore, each subcategory also contains emission standards i.e., the euro standard ratings euro 1-6. Besides, they calculate the emission and fuel consumption of a vehicle based on the average driving speed, loading levels, urban share, etc. The COPERT software has the advantage of calculating the national emission inventory directly (along with the total fuel consumption), if the annual mileage of each vehicle type and the number of vehicles is input into it. In addition to this, COPERT provides data on emission of 26 different pollutants.

Due to the above stated advantages, COPERT is chosen as the vehicle emission inventory database and the software of choice. Figure 3.2 shows the main inputs and outputs of the model, with e_i, d_i and n_i corresponding to the variables in eq 3.1. The individual terms in fig 3.2 is explained in detail section 3.2.1.2. Data on ambient conditions are necessary for evaluating the energy needs of Air Conditioning system in the vehicle needs and to calculate the emissions from fuel evaporation [58].

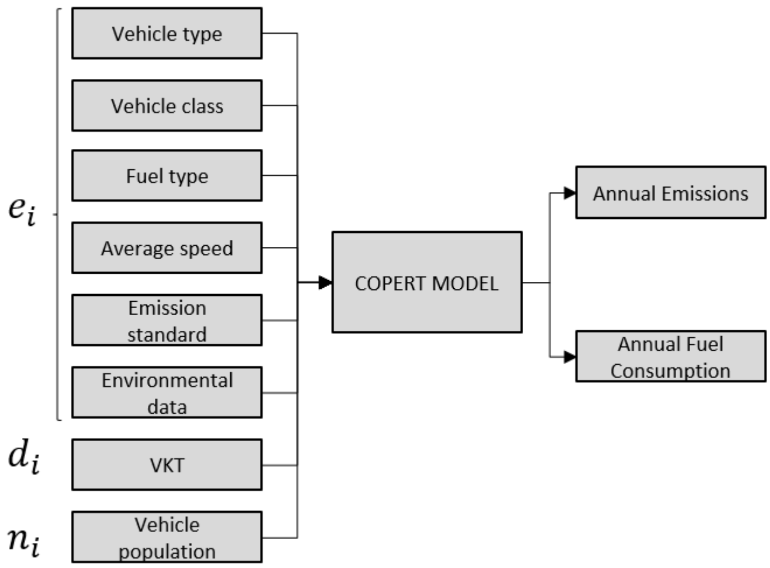

Figure 3.2: Inputs and Outputs of the COPERT model

The information on the inputs to this model will be discussed in the section 3.2.1.2. Figure 3.3 shows the 26 different emissions that are available in COPERT. Each emission has a different environmental impact. They have been grouped into GHGs, acidic gases, PM emissions and others.

GHGs	Acidic Gases	PM emissions	Others
CO_2, N_2O, CH_4	SO_2, NO_x (NO, NO_2), NH_3	PM 2.5, PM TSP, PM 10	As, Black Carbon (BC), Cd, CO, Cr, Cu, Hg, Ni, NMVOC, Organic Material (OM), Pb, Se, VOC, Zn

Figure 3.3: Emission inventory provided by COPERT

For evaluating the environmental impact of the individual GHGs/pollutants, numerous climatic models are available. In life cycle assessment terms, they are known as life cycle impact assessment methods (LCIA) [53]. The GHG emissions are normalised into a single category, viz. climate change. The impact assessment method of choice for climate change (caused by GHGs) is ILCD midpoint 2011+. The normalisation factor (NF) used for the emissions are CO_2 (1), N_2O (298) and CH_4 (25) [59], [60]. The acidic gases are normalised to their acidification potential (AP) based on the following normalisation factors: SO_2 (1), NO_x (0.5) and NH_3 (1.6). The impact assessment method based on which these factors were chosen is CML-IA baseline [61]. The direct PM 2.5 emissions shall be investigated as well. These values are tabulated in Table 3.1. As discussed in the chapter 2, the primary results shown and discussed in this thesis will be based on GHG emissions. However, the AP and PM emissions are also evaluated, and the results are presented as and when needed.

Climate Change		Acidification Potential	
Pollutant	**NF**	**Pollutant**	**NF**
CO_2	1	SO_2	1
CH_4	25	NO_X	0.5
N_2O	298	NH_3	1.6
Method	ILCD midpoint 2011+	Method	CML IA Baseline

Table 3.1: Normalisation factors for the pollutants across different impact categories

Most of the emissions in the section 'others' is related to human toxicity (both cancerous and non-cancerous effects). As discussed in the introduction, this is left out of the scope of this work. The emissions involved in manufacturing of the vehicle is also beyond the of scope of this work.

3.2.1.2 Data Acquisition

In this section, the data inputs necessary for evaluation of the national emission inventory as per Figure 3.2 and equation 3.1 is discussed. This work is divided into 2 sections. In the first section (3.2.1.2.1), the acquisition of raw data from the nation's annual vehicle statistics shall be covered. In the second section (3.2.1.2.2), an analysis on how this data needs to be modified to get vehicle population at a finer resolution (i.e., classified by engine size and emission standards), to be input into COPERT is done. Parts of the work done in this section was done by Mr Yashwin Iddya for his Master Thesis under my supervision [52]. The work has been adopted and modified to suit this thesis better. For the sake of a better understanding, a few terms that are specific to COPERT are defined below.

Vehicle type: Refers to the type of vehicle under consideration viz. PC, LCV, Bus, Trucks, MCs and Taxis. Though both Taxi and PC refer to a car, a differentiation is made as their VKTs might differ.

Vehicle classes: This refers to the size of each vehicle type. For example, a passenger car is classified into mini, small, medium and large based on its engine size. A truck is classified based on its tonnage.

Fuel type: Refers to the kind of fuel used (Diesel or Petrol) for each vehicle type.

Average speed: This refers to the average speed of each vehicle type.

Environmental data: Refers to the monthly maximum and minimum temperatures and the relative humidity (RH) of each country.

Emission standards: This refers to the emission standards (Euro) for each vehicle type.

VKT: This refers to the annual VKT for each vehicle type.

Vehicle population: This refers to the number of vehicles for each vehicle type.

3.2.1.2.1 Collection of raw data

As stated before, the data acquisition is categorised into 2 sections. The first section deals with acquisition of vehicle population, ambient conditions, VKT and vehicle speeds from nation's annual vehicle statistics. The data acquisition is divided and discussed through each country as the methodology differed greatly between the countries. There are a few assumptions made, the reasoning of the same has been discussed too. All the data is collected for the reference year 2014.

Brunei Darussalam (BRN): The information on vehicle population, engine classes, fuel type, etc, is available on a detailed level from the Land Transport Department, under Ministry of Communication for Brunei [62]. Annual VKT is derived from [63]. The environmental data is derived from [64].

Cambodia (KHM): Vehicle population for the year 2013 is taken from World Health Organisation [65]. By adding new registration in the year 2014 as given by C. Vannak [66] to the 2013 data, vehicle population for 2014 is achieved. The VKT is derived from [63]. The average monthly environmental data for Phnom-Penh is derived from [64] and applied to entire Cambodia.

Indonesia (IDN): Central Bureau of Statistics provides the data on vehicle population [67]. The data on fuel share and VKT is taken from the CAA tool [63]. The average vehicle speed of a PC is assumed to be 25 kmph (based on the values for different Indonesian cities) [68]. All other vehicles are expected to behave like PC. For bus alone, a correlation factor of 0.71 with PC speed was chosen from [69]. The environmental data for Indonesia is assumed to follow that of Jakarta which is taken from [64] .

Laos (LAO): Vehicle population for Laos is derived from the Laos Statistical Bureau [70]. While assuming the trucks and buses are diesel and MC are petrol and the passenger cars is based on the fuel share split based on [71]. The VKTs are derived from [72] and the average speed for vehicle in Vientiane [73] is used as representative for the whole population. The environmental data for Vientiane is derived from [64] and is used to represent entire Laos.

Malaysia (MYS): In its annual statistics, The Road Transport Department of Malaysia provides data on vehicle population [74]. The fuel share of vehicle types has been taken from [75]. Since the data on average vehicle speeds are not available, it is assumed to have a similar distribution of that of Indonesia. The average speeds of MCs alone are taken from [76]. The VKT for the different vehicle types are derived from [63], [77]–[79]. The environmental data for Kuala Lumpur is derived from [64] and assumed to be representative of Malaysia.

Myanmar (MMR): The vehicle population is derived from the vehicle registration data provided by Myanmar Statistical Information Service [80]. Hlaing et al. provide the fuel share for different vehicle types [81]. The VKT is available from [63], [82], the values are chosen based on validation of model discussed in section 3.3.4. The vehicle speed is assumed to be like that of Indonesia because of lack of local data. The environmental data is derived from [64].

Philippines (PHL): Data on the vehicle population for 2014 for Philippines is not available directly. Hence it is derived by combining the data from Department of Land Transport, Philippines (which has the dataset for 2013) [83] and the Land Transport office (which has the vehicles sales data for 2014) [84]. The fuel share for the different vehicle categories was derived from [85]. The annual VKTs are derived from [63], [86] and validated through the validation study (section 3.3.4). The average speeds of Manila [87] are assumed to represent the whole of Philippines. The environmental data is derived from [64].

Singapore (SGP): The Land Transport Authority (LTA) of Singapore provides most of the data necessary. Annual vehicle statistics [88] provides data on the necessary population of the different vehicle types, classifying it by the fuel type as well [89]. The tax exempted vehicles are left out of the valuation as enough details are available for them. These contribute to a meagre 2% of the entire fleet and hence would not affect the results largely. The annual VKT for different vehicle types is also provided by LTA [90]. For taxis which have annual mileages larger than a normal passenger car, the data is derived from [91]. The average vehicle velocity is derived from [69]. The environmental data of Singapore is acquired from [92].

Thailand (THA): Vehicle population for Thailand is taken from the Department of Land Transport, Thailand [93]. Ministry of Transport's annual statistics [94] provides data on VKT. As vehicle speeds is not available, the data from Indonesia is used for Thailand. The environmental data for Bangkok is derived from [64] and is assumed to represent entire Thailand.

Viet Nam (VNM): For Viet Nam, the vehicle population and classification of vehicle types is not directly available. Hence it was taken from multiple data sources namely [95]–[98]. A more detailed description of the methodology is found in [52]. The fuel share of vehicles is retrieved from [99] through linear interpolation. The VKT is derived from [63], [100]. The average speed is given for different types of road in [98], the road lengths from [101] is used to derive the average speed at the country level. The environmental data is derived from [64].

An assimilation of all the data derived using the above methodology and corrected by validation method (section 3.3.4) is shown in Table 3.2 & Table 3.3 and Figure 3.4 - Figure 3.6.

	PC	Taxi	Bus	LCV	Trucks	MC
BRN	265.6	0.0	2.0	2.6	10.3	4.5
KHM	373.0	0.0	4.5	0.0	45.6	2352.9
IDN	12599.0	0.0	2398.8	327.2	5907.9	92976.2
LAO	73.8	0.0	56.3	185.1	44.3	1218.4
MYS	8043.3	118.2	46.7	613.9	219.0	8351.6
MMR	429.5	0.0	26.7	139.8	51.3	4276.7
PHL	1284.0	1859.1	31.4	0.0	408.1	4496.2
SGP	606.6	28.7	17.1	95.6	48.9	144.4
THA	7284.3	308.7	567.5	5954.2	1007.6	20141.2
VNM	840.4	0.0	102.0	439.9	285.8	39074.5

Table 3.2: Vehicle population for the ASEAN Countries (in thousands)

A peculiar aspect about ASEAN nations is the share of MCs they use. Barring Singapore and Brunei which are dominated by PCs, MCs dominate the vehicle share for all other ASEAN nations.

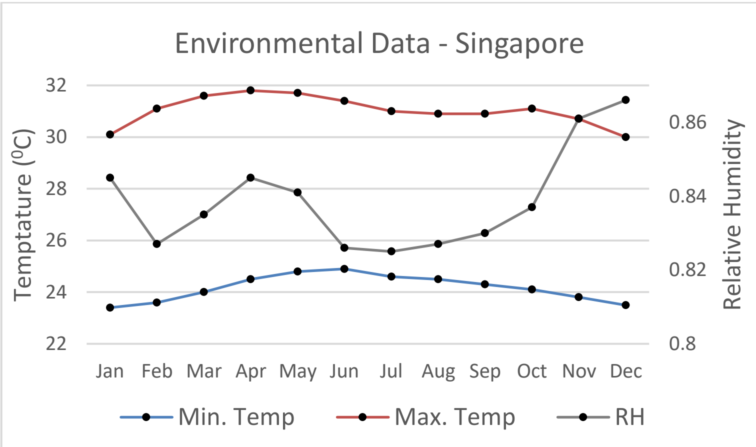

Figure 3.4: Climatic variation in Singapore

The variations in the ambient conditions for Singapore is shown in the Figure 3.4. A large variation in ambient conditions across the month is not seen. A similar trend is observed across all the ASEAN nations as they are in the equatorial region.

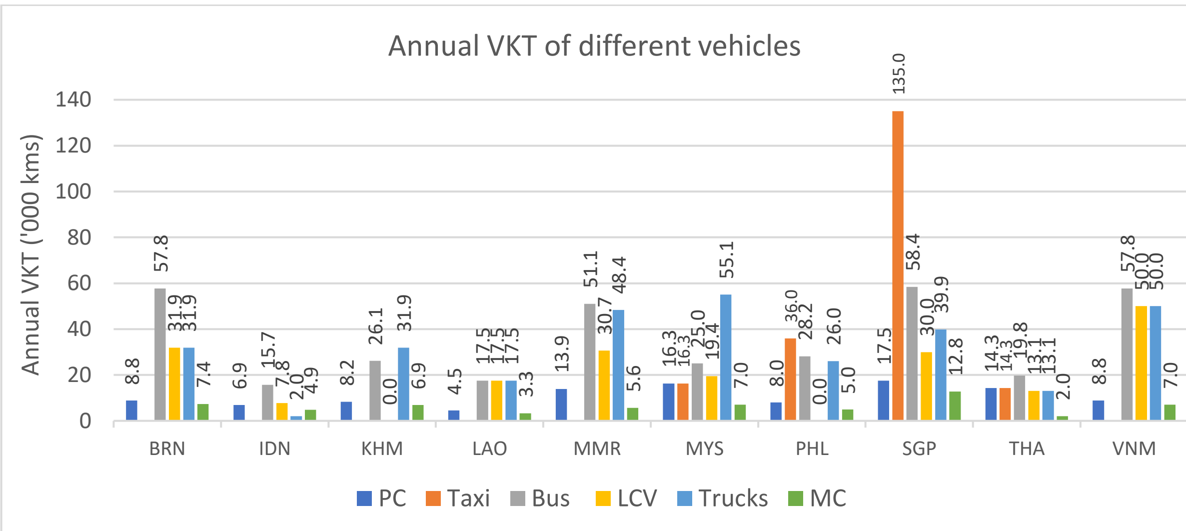

Figure 3.5: The annual VKT for different vehicles for different countries ASEAN

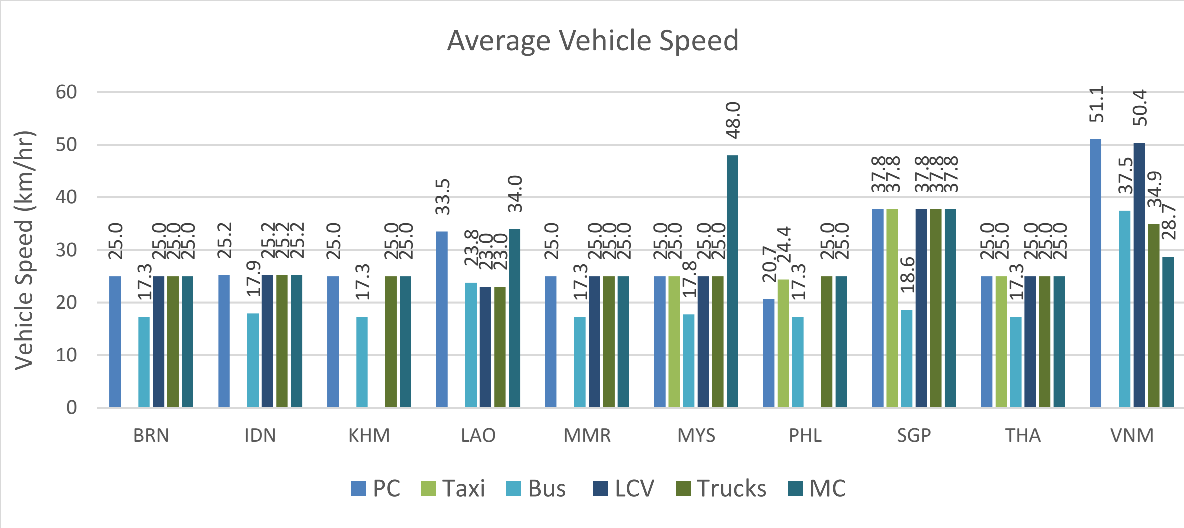

Figure 3.6: The average speeds of different vehicles for different countries in ASEAN

Fig 3.5 and Fig 3.6 gives generic data on annual VKTs and vehicle speeds for different ASEAN nations. However, there are a few small deviations observed for specific vehicle types. In Malaysia, the VKT of a large PC is 9,100 km (and not 16,315 km). For Philippines, the average speed of a large PC is 19 km/hr.

Unit:%	PC		Taxi		Bus		LCV		Trucks		MC
	P	D	P	D	P	D	P	D	P	D	P
BRN	81.1	18.9			0.0	100.0	0.0	100.0	0.0	100.0	100.0
IDN	100.0	0.0			0.0	100.0	0.0	100.0	0.0	100.0	100.0
KHM	72.0	28.0			0.0	100.0			0.0	100.0	100.0
LAO	69.5	30.5			0.0	100.0	30.5	69.5	0.0	100.0	100.0
MMR	58.4	41.6			0.0	100.0	22.9	77.1	4.6	95.4	100.0
MYS	99.5	0.5	99.2	0.8	1.1	98.9	26.3	73.7	24.4	75.6	100.0
PHL	76.9	23.1	20.0	80.0	0.0	100.0			0.0	100.0	100.0
SGP	99.4	0.6	14.7	85.3	0.0	100.0	8.0	92.0	0.0	100.0	100.0
THA	75.2	24.8	99.3	0.7	13.2	86.8	7.0	93.0	0.1	99.9	100.0
VNM	83.8	16.2			0.0	100.0	20.0	80.0	0.0	100.0	100.0

Table 3.3: Vehicle Share by fuel type for different countries in ASEAN

In the next section (3.2.1.2.2), the vehicles will be classified by vehicle classes and emission standards. Here, not a great quality of data is available for all the nations. Hence, it is dealt with separately.

3.2.1.2.2 Classification of vehicles based on classes and emission standards

The fuel consumption and emissions of a vehicle type largely depends on its size/class of a vehicle as well. For instance, the emissions of a small car with an engine capacity of less than 800cc would be very different from that of a large car with a capacity greater than 2000 cc. Hence, there is a necessity to classify the vehicles across its classes in order to estimate the emissions and fuel consumption more accurately. Similarly, the emission standard (euro class) of a vehicle influence the amount of emissions they produce. In this section, a discussion on how the vehicle population is distributed into vehicle size and emission standards, as per the requirement of COPERT is carried out.

Vehicle Classes: COPERT provides standard vehicle classes for different vehicle types. While PCs and MCs are classified based on engine sizes, LCV, truck and buses are based on their tonnages. Of the various vehicle classes available in COPERT, the relevant ones considered in this work are shown in the Figure 3.7.

PC/Taxi	LCV	Truck	Bus	MC
• Mini (<800 cc) • Small (801-1400 cc) • Medium (1401-2000cc) • Large (>2000cc)	• LCV N1 (<1305 kg) • LCV N2 (1305 - 1760 kg) • LCV N3 (1761-3500 kg) • LCV > 3.5 t	• Rigid <=7,5 t • Rigid 7,5 - 12 t • Rigid 12 - 14 t • Rigid 14 - 20 t • Rigid 20 - 26 t • Rigid 26 - 28 t • Rigid 28 - 32 t • Rigid >32 t • Articulated 40-50 t	• Urban Buses Midi (<=15 t) • Urban Buses Standard (15 - 18 t) • Urban Buses Articulated (>18 t) • Coaches Standard (<=18 t) • Coaches Articulated (>18 t)	• Small (<250cc) • Medium (251-750) • Large (>750)

Figure 3.7: Different vehicle classes considered

There are two issues with classifying the vehicle population based on classes. The first one is that the vehicle classes available from national databases are not in the same category as the one available in COPERT. This issue is solved by assuming a linear distribution of vehicles across the category (i.e., engine size or tonnage). The numbers are then accumulated into the category available in COPERT. An example is shown below (in Figure 3.8 and Table 3.4) for passenger cars in Singapore.

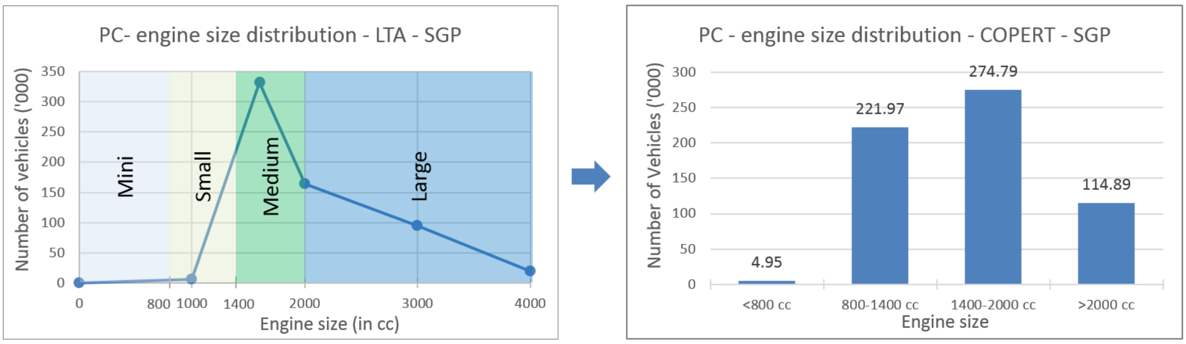

Figure 3.8: Linearization of vehicle classes

LTA Statistics - SGP		COPERT	
Categories	**Original Data**	**Categories**	**Adjusted Data**
1000 cc & below	6,189	800 cc & below	4,951
1001 - 1600 cc	331,104	801-1400 cc	221,974
1601 - 2000 cc	164,424	1401 - 2000 cc	274,792
2001 - 3000 cc	95,251	2001 cc & above	114,892
3001 cc & above	19,641		

Table 3.4: Adopting vehicle classification into COPERT [88]

The second issue is that the vehicle classes distribution data is not available for all the countries. In this case, vehicle class distribution is assumed to either follow that of another country or the median value. The vehicle classes for PCs are available for Singapore, Malaysia, Indonesia, Vietnam, Philippines and Brunei [62], [74], [85], [88], [97], [102]. They are plotted as shown in Figure 3.9. It is observed that most of the PCs fall in the small and medium range. Vietnam and Philippines alone prefer larger vehicles. For the other countries, viz. Thailand, Cambodia, Laos and Myanmar, the distribution of Malaysia is assumed.

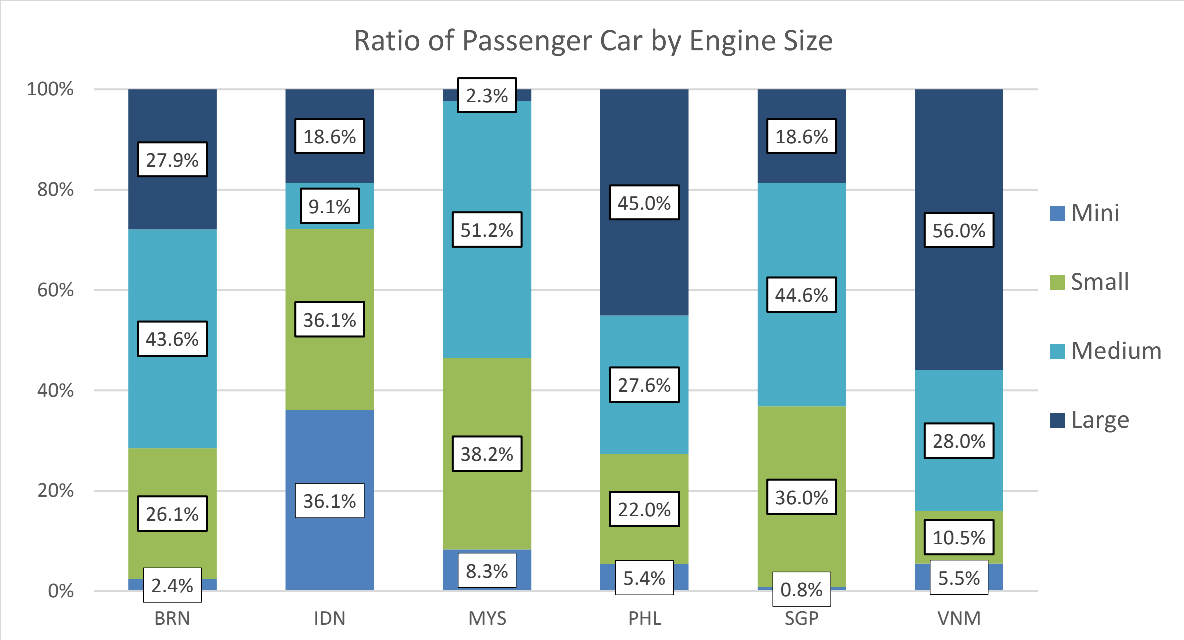

Figure 3.9: Ratio of passenger car by its engine size for various ASEAN countries.

The engine size distribution of MCs is available for the countries Singapore, Malaysia, Vietnam and Brunei and plotted below in Figure 3.10 [62], [74], [88], [102]. It is observed that majority of countries have MCs lesser than 250 cc. Small MCs form a major mode of transportation for a large group of vehicles in ASEAN countries. The distribution of Malaysia is adopted for all the remaining nations, for which the data is not available.

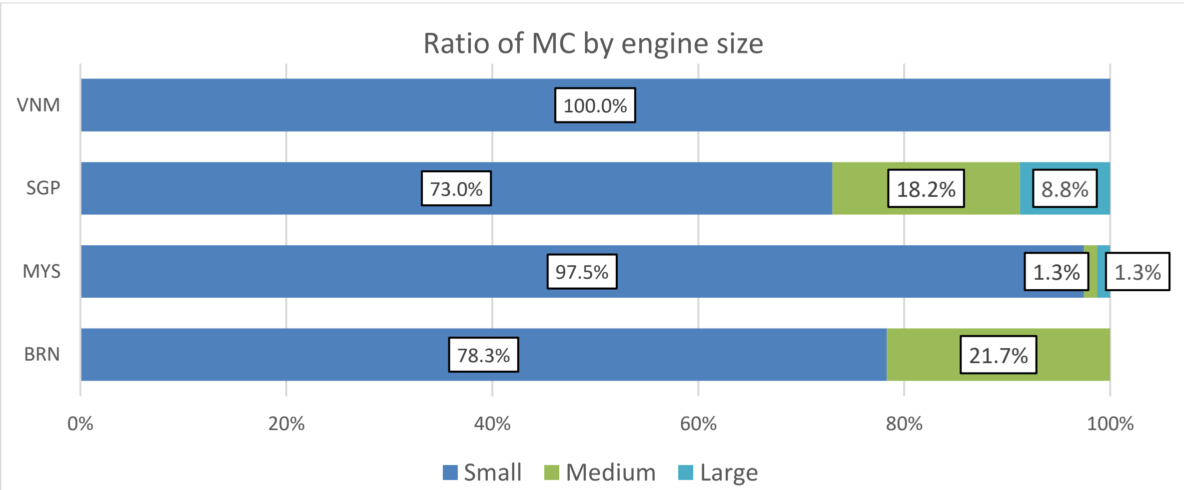

Figure 3.10: The Ratio of MCs by their engine size

Data on distribution of Trucks based on its classes is available only for Singapore, Thailand and Indonesia [88], [93], [102] and is plotted in Figure 3.11. The trend observed is that most of the trucks belong to the smallest category and the number keeps decreasing with increasing truck size. The distribution of Singapore is assumed for all the other counties.

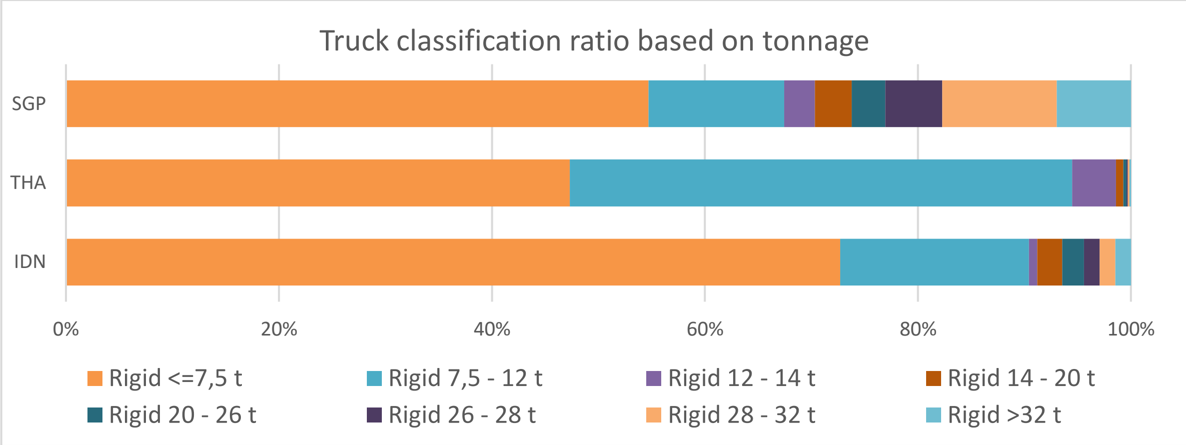

Figure 3.11: Percentage of trucks based on their tonnage for different ASEAN Countries

Distribution of buses across its category is available for Singapore Malaysia and Indonesia and plotted in Figure 3.12 [74], [88], [102]. A clear trend is not observed here. Hence, for the other nations, it is assumed the buses to fall in the middle range, i.e., 15-18 t category.

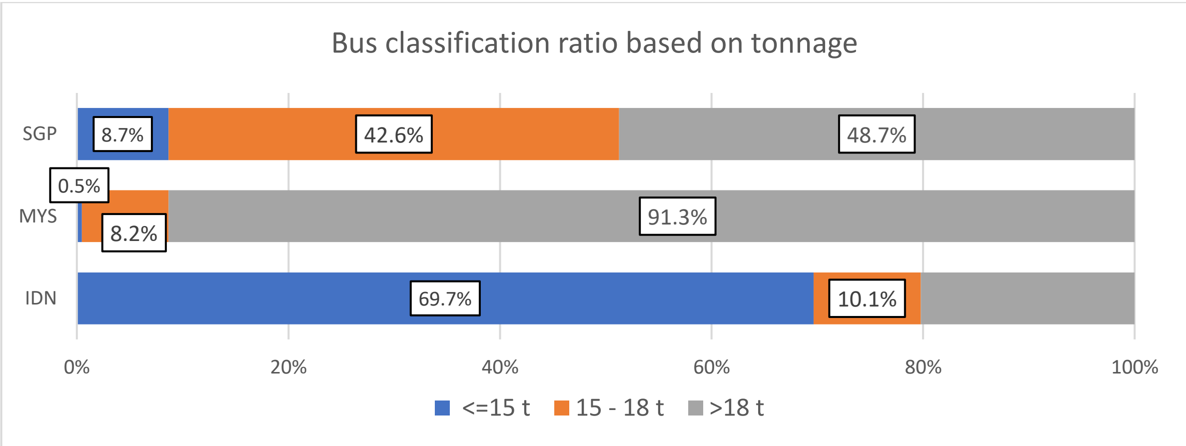

Figure 3.12: Percentage of buses based on their tonnage for different ASEAN countries

Emission Standards: COPERT has a database of emission of different vehicles based on their Euro emission standards. Further to the classification of vehicles based on fuel type and classes, they are classified based on the Euro emission standards as well. The data on the year of implementation of Euro standards in different countries is found from various data sources [63], [102]–[109] and is plotted in Figure 3.13. Based on the age of the vehicle data collected either from national inventories or vehicle sales data for different countries, the vehicles have been classified by their emission standards.

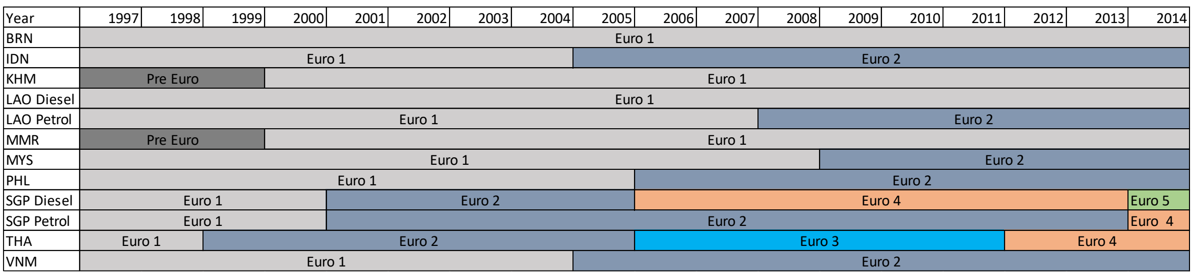

Figure 3.13: Year of implementation of Euro Standards in ASEAN nations.

3.2.2 Well to tank emissions of the fossil fuels

The well to tank emissions deals with the emissions and energy needs involved with bringing the fuel (petrol/diesel) to the vehicle. As seen from Figure 3.1, the general processes involved with production and fuelling of the vehicle are, crude extraction, refining, shipping to the country followed by transportation to the fuel pumps. Each of the processes involve many sub processes in them. Thus, the entire chain becomes complicated to evaluate, especially when dealing with 10 different nations. Southeast Asian nations import crude (and refine it within the nation) as well as refined products (i.e., petrol and diesel). There are a few countries such as Indonesia, Malaysia, etc., which produce their own crude and refined products as well. Furthermore, there is trade (of both crude and refined products) that happen between the ASEAN countries. This import or production profile of crude or refined products varies largely among the countries. For instance, Singapore is completely dependent on import with 30% of it being crude import and the rest 70% being import of refined products [110]. Whereas Malaysia imports 59% (13% crude and 45% refined products) and produces 41% of the refined products within the country using their own resource. The place of import for each country varies vastly as well. The emissions and energy consumption of the crude extraction varies largely between the extraction sites based on the methodology and technology used. There is a large variation between the refineries as well. As each country imports from a different country the international transport distances vary largely. The inland transportation from ports to petrol pump is also a variable.

An effort was made to map the crude and refinery products flow into ASEAN countries, as a part of the Master Thesis of Mr Yashwin Iddya. The well to tank emissions of diesel and petrol in each country was calculated based on this flow. One can refer to the thesis for a detailed explanation of the process [52]. However, due to the large amount of assumptions made and simplifications done, it was assessed that such an approach might not yield highly reliable results. Hence, in this thesis, the approach is simplified by retrieving the values of well to tank emissions of petrol and diesel manufacturing from literatures/standard databases. This would increase the reliability of the study. There are standard databases such as ecoinvent, GREET, U.S. Life Cycle Inventory Database (USLCI), European Life Cycle Database (ELCD), etc, which gives value of emissions of different pollutants per unit fuel produced. Table 3.5 and Table 3.6 show the emissions involved in production of a MJ of diesel and petrol respectively, with the data being taken from different sources.

Diesel		Factors from different sources				
Entity	**Unit**	**ecoinvent-RoW**	**ecoinvent-GLO**	**GREET**	**Publication**	**USLCI**
GHG	*(g CO_2eq/MJ)*	13.9	13.7	17.3	25.6	12.5
AP	*(g SO_2eq/MJ)*	0.142	0.14	0.0147	0.0635	0.0174
PM	*(g PM 2.5/MJ)*	6.81E-03	6.57E-03	1.64E-03	0.00E+00	0.00E+00

Table 3.5: WTT emissions of diesel production

Petrol		Factors from different sources				
Entity	**Unit**	**ecoinvent-RoW**	**ecoinvent-CH**	**GREET**	**USLCI**	**ELCD**
GHG	*(g CO_2eq/MJ)*	19.8	18.3	21.0	12.5	15.9
AP	*(g SO_2eq/MJ)*	0.177	0.166	0.0219	0.173	0.096
PM	*(g PM 2.5/MJ)*	9.07E-03	6.88E-03	3.01E-03	0.00E+00	3.21E-04

Table 3.6: WTT emissions of petrol production

It was decided to adhere to ecoinvent for the following reasons:

1) It is the most complete and widely used database.
2) It entails the entire upstream processes involved with petrol/diesel production with the greatest detail.
3) Data from ecoinvent is used in the other parts of the thesis as well. Hence it would be easier to maintain the consistency (of product system and allocation method) through the thesis.

The terms RoW, GLO and CH represents rest of world, global and Switzerland respectively. For this thesis, the upstream emissions of diesel/petrol production are taken from ecoinvent-RoW. The name of the specific process is “Petrol, low-sulfur {RoW}| market for | Cut-off, U” and “Diesel, low-sulfur {RoW}| market for | Cut-off, U”.

3.3 Vehicle and emission inventory in ASEAN - Results

PC	**Petrol**			**Diesel**				**Total**
	Euro 1	**Euro 2**	**Euro 4**	**Euro 1**	**Euro 2**	**Euro 4**	**Euro 5**	
Mini	0	0	4909	0	0	25	0	
Small	2916	204971	12171	16	145	946	54	
Medium	3610	253744	15066	19	180	1171	66	**614510**
Large	1509	106092	6299	8	75	490	28	
Total	8035	564807	38445	43	400	2632	148	

Taxi	**Petrol**			**Diesel**				**Total**
	Euro 1	**Euro 2**	**Euro 4**	**Euro 1**	**Euro 2**	**Euro 4**	**Euro 5**	
Mini	0	0	0	0	0	0	0	
Small	3	188	602	121	1128	7348	417	
Medium	3	228	728	146	1366	8898	505	**26645**
Large	1	95	305	61	571	3720	211	
Total	7	511	1635	328	3065	19966	1133	

MC	**Petrol**			**Diesel**				**Total**
	Euro 1	**Euro 2**	**Euro 4**	**Euro 1**	**Euro 2**	**Euro 4**	**Euro 5**	
Small	105460	0	0					
Medium	26289	0	0					**144405**
Large	12656	0	0					
Total	144405	0	0					

LCV	**Petrol**			**Diesel**				**Total**
	Euro 1	**Euro 2**	**Euro 4**	**Euro 1**	**Euro 2**	**Euro 4**	**Euro 5**	
LCV N1 <1305kg	575	2031	219	6625	10651	12746	2518	
LCV N2 1306-1760	202	714	77	2328	3742	4478	885	**95580**
LCV N3 1761-3500	777	2745	295	8952	14393	17224	3403	
Total	1554	5490	591	17905	28786	34448	6806	

Truck	**Petrol**			**Diesel**				**Total**
	Euro 1	**Euro 2**	**Euro 4**	**Euro 1**	**Euro 2**	**Euro 4**	**Euro 5**	
Petrol > 3,5 t	0	0	0	0	0	0	0	
Rigid <=7,5 t				4901	7879	9429	1863	
Rigid 7,5 - 12 t				1142	1836	2179	434	
Rigid 12 - 14 t				257	414	495	98	
Rigid 14 - 20 t				309	497	595	118	
Rigid 20 - 26 t				284	457	547	108	**48900**
Rigid 26 - 28 t				483	776	928	183	
Rigid 28 - 32 t				965	1552	1857	367	
Rigid >32 t				623	1002	1199	237	
Articulated 40 - 50 t				995	1599	1914	378	
Total	0	0	0	9959	16012	19143	3786	

Buses	**Petrol**			**Diesel**				**Total**
	Euro 1	**Euro 2**	**Euro 4**	**Euro 1**	**Euro 2**	**Euro 4**	**Euro 5**	
Urban Midi <=15 t				269	241	831	143	
Urban Std. 15 - 18 t				1318	1184	4075	704	**17098**
Coach Art. >18 t				1508	1355	4664	806	
Total				3095	2780	9570	1653	

Table 3.7: Vehicle population in Singapore classified by vehicle type, classes and fuel type

3.3.1 Vehicle inventory database

Table 3.7 provides the population different vehicle types (PC, Taxi, MC, LCV, Truck and Bus) and their split across different classes and emission standards for Singapore. These stand as the input for the COPERT model. The database for the other countries is found in Appendix (Table A.1 to Table A.9).

3.3.2 Tank to wheel emissions

Figure 3.14 shows the ratios of tank to wheel GHG emissions of vehicles in Singapore. The emissions are classified through different vehicle types, fuel type and vehicle classes. Similar results for AP and PM emissions are available in appendix (Figure A.1 and Figure A.2). These emissions represent the on-road vehicle emissions caused by driving of the vehicle in Singapore. The split between the different vehicle classes is also seen.

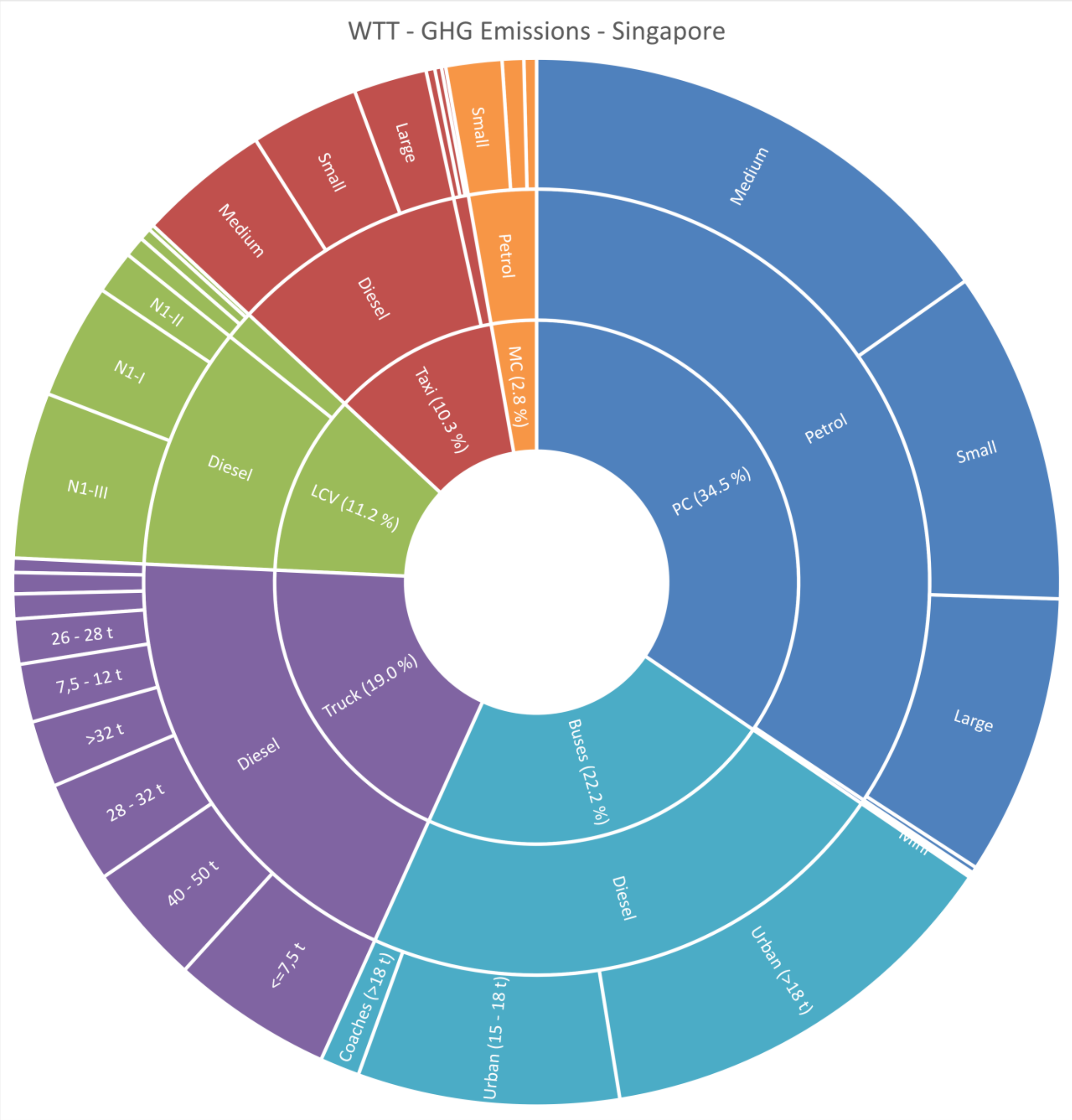

Figure 3.14: Ratio of TTW GHG emissions of vehicles in Singapore classified by vehicle types, classes and fuel type

3.3.3 Well to wheel emissions

The national GHG emissions of vehicle in ASEAN countries is shown in Figure 3.15. Indonesia being the largest country by size and population produces the greatest amount of emissions. Though Thailand is not the second most populated country, it produces the second largest emissions in ASEAN due to its higher level of economic development. On the other hand, though Cambodia, Myanmar and Laos have large land areas and are well populated, they have very low per capita emissions as they are less developed. The level of development not only dictates the level of mobility but also the vehicle type mix of the country. More developed countries like Singapore, Brunei, Malaysia, etc. use cars for their mobility, increasing their per capita emissions. They also do a lot of transportation of goods. On the other hand, less developed nations like Cambodia, Myanmar, Vietnam use a lot of MCs and hence have a lower per capita emission. The national emissions of acidic gases and PM 2.5 emissions are given in appendix (Figure A.3 and Figure A.4).

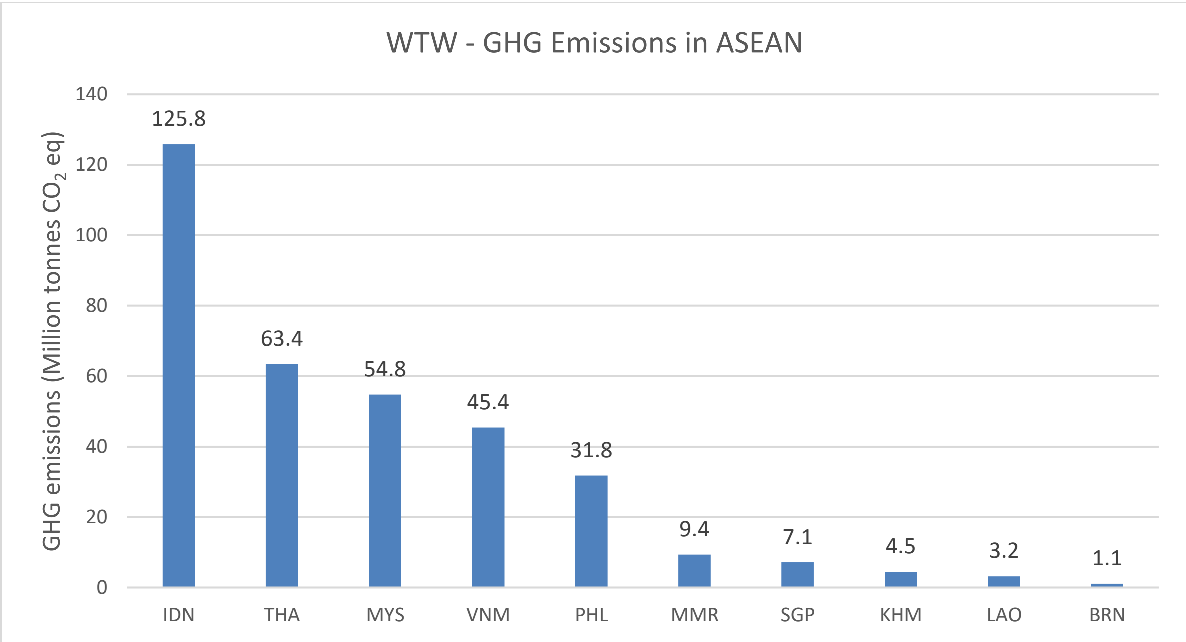

Figure 3.15: WTW GHG Emissions of ASEAN Nations

Figure 3.16, Figure 3.17 and Figure 3.18 shows the ratio of well to wheel emissions of GHG, AP and PM of vehicles in Singapore. The emissions are classified through different vehicle types and fuel type only. The classification by vehicle size is removed for a simpler representation.

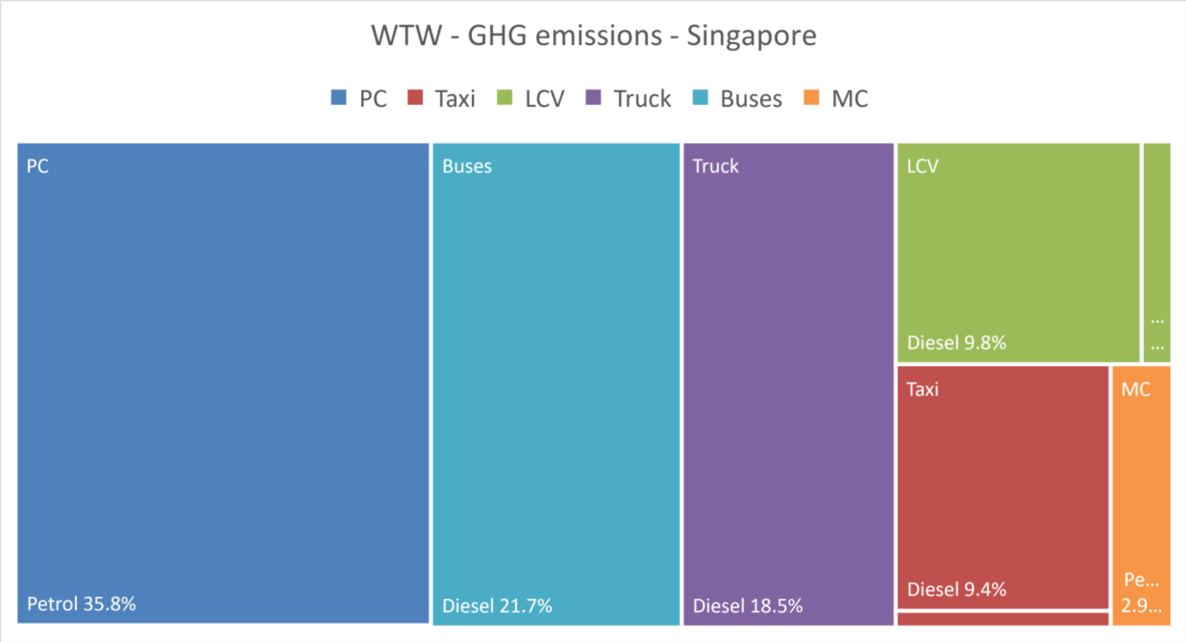

Figure 3.16: WTW GHG emissions of different vehicle types in Singapore

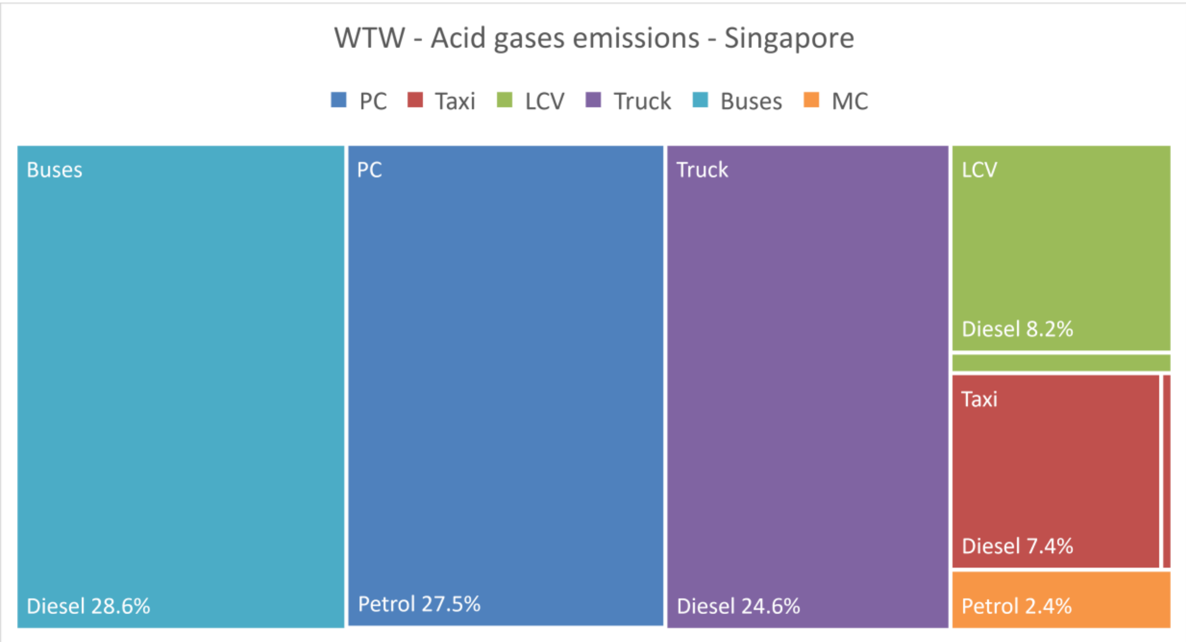

Figure 3.17: WTW emission of acidic gasses of different vehicle types in Singapore

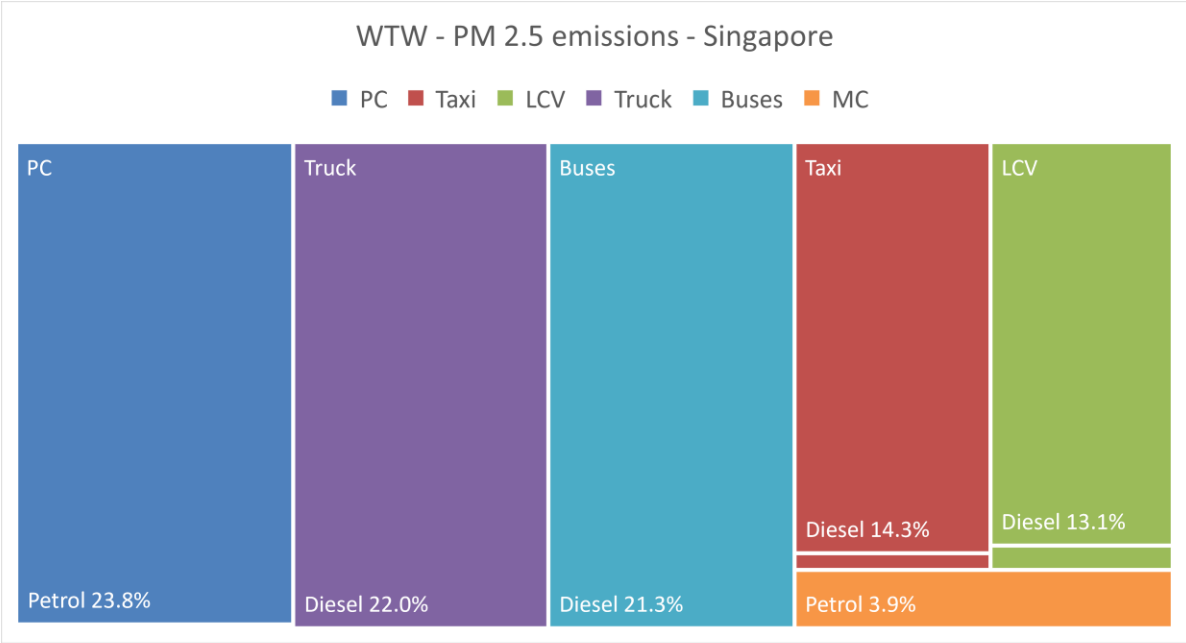

Figure 3.18: WTW PM 2.5 emission of different vehicle types in Singapore

When it comes to GHG emissions in Singapore, PC contribute to the most (35.9%) with 35.8% of it coming from petrol cars. Diesel buses contribute to 21.7% of the emissions and followed by diesel trucks at 18.5%. Contribution from taxis are approximately 10%, most of them being diesel powered. Singapore is a highly developed and a densely populated city state which has good road public transport and taxi network. Hence these numbers from PCs, Buses and taxis are justified. When it comes to AP emissions, a slight change in the trend is observed. Diesel Buses contribute the most, the reason being higher NO_x emission from the diesel engine. The next biggest contribution for AP emissions comes from petrol PCs. Though petrol vehicles do not contribute greatly to NO_x emissions, the high number of PCs and their higher annual mileage contribute to the bigger percentage. Diesel trucks emit a lot of NO_x emissions as well. A similar trend is seen in PM 2.5 emissions as well with petrol PCs, diesel trucks and diesel buses contributing to roughly 22% each.

In general, a variation can be found between GHG, AP and PM emissions. GHG depends mainly on the fuel consumption (which depends on annual mileage and vehicle population). Though diesel engines are slightly more efficient than petrol engines, the difference in GHG emission profiles of petrol and diesel vehicles are not starkly different. Whereas the AP and PM emission profiles between diesel and petrol vehicles varies greatly, with diesel engines producing higher emissions per unit distance travelled.

Figure 3.19 provides the ratio of GHG emissions from different vehicle types in the different ASEAN nations. Emissions from PCs dominate in Singapore, Malaysia and Brunei which are mostly petrol driven. Countries such as Vietnam, Myanmar and Cambodia are dominated by the emission of petrol driven MCs. Contribution from diesel trucks and buses are considerable too. There are some uncommon trends observed as well. For instance, LCVs in Thailand contribute to 37.3% of its national emissions. Similarly, diesel taxis in Philippines contribute to 43% of their emissions. The profiling and evaluation of emissions is important as it helps identify the mitigation potential.

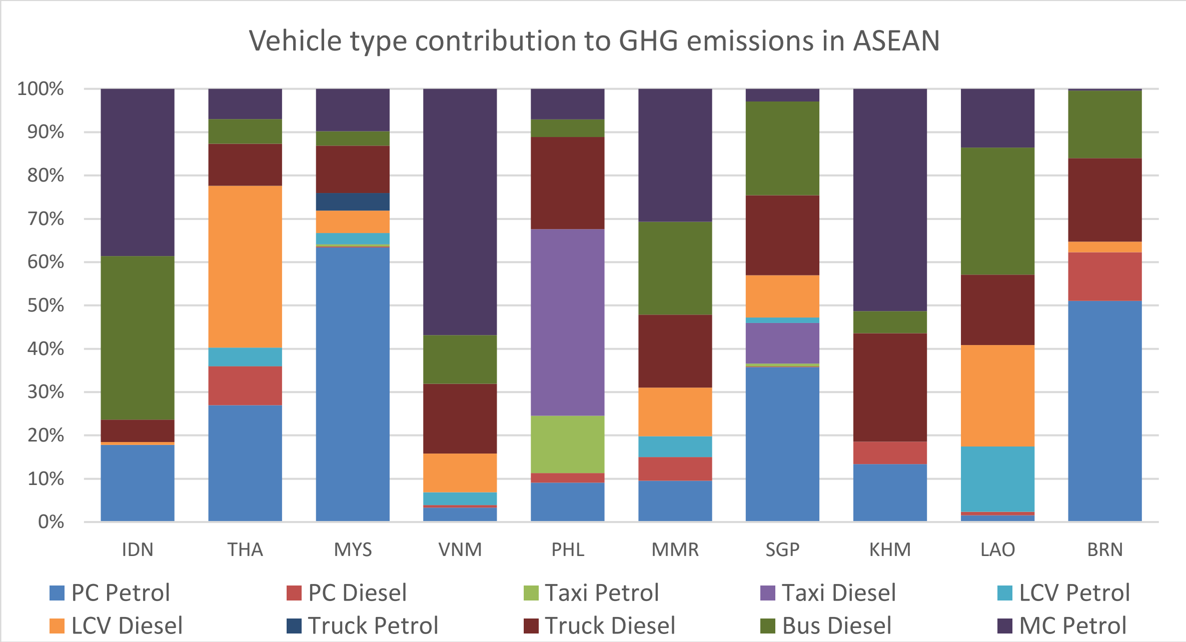

Figure 3.19: Contribution of different vehicle types towards the WTW GHG emissions

3.3.4 Validation of the model developed

In this section, the model built is validated. As already discussed, there are a few assumptions and simplifications made in our model. As the national emission inventories (and subsequently the emission reduction potential evaluation) depends on the model built, its validation becomes essential. Fuel consumption is chosen as the validation parameter for the model. The reason for this is that the data on emissions are not available at national level, at the resolution that is required. Also, experience dictates that, the fuel consumption is the most reliable part of any vehicle emission model. The primary reason for the same being the fuel consumption model is more consistent across different studies (with emission evaluation differing between the models). The fuel consumption derived in our model is compared against the fuel consumption data found in

1) Clean Air Asia (CAA) Model and
2) National statistics (UN/IEA)

The CAA model [63] is straightforward and gives the national level fuel consumption of road transport split into petrol and diesel. The national statistics are available from several sources. For the sake of uniformity, the national statistics is taken either from United Nations (UN) Energy Statistics [111] or IEA [112]. The below figures compare the above-mentioned energy sources with the fuel consumption derived from my model. For accommodating different scales, the nations are split into two groups viz. group 1 (comprising of Indonesia, Thailand, Malaysia, Vietnam and Philippines) and group 2 (comprising of Myanmar, Singapore, Cambodia, Laos and Brunei).

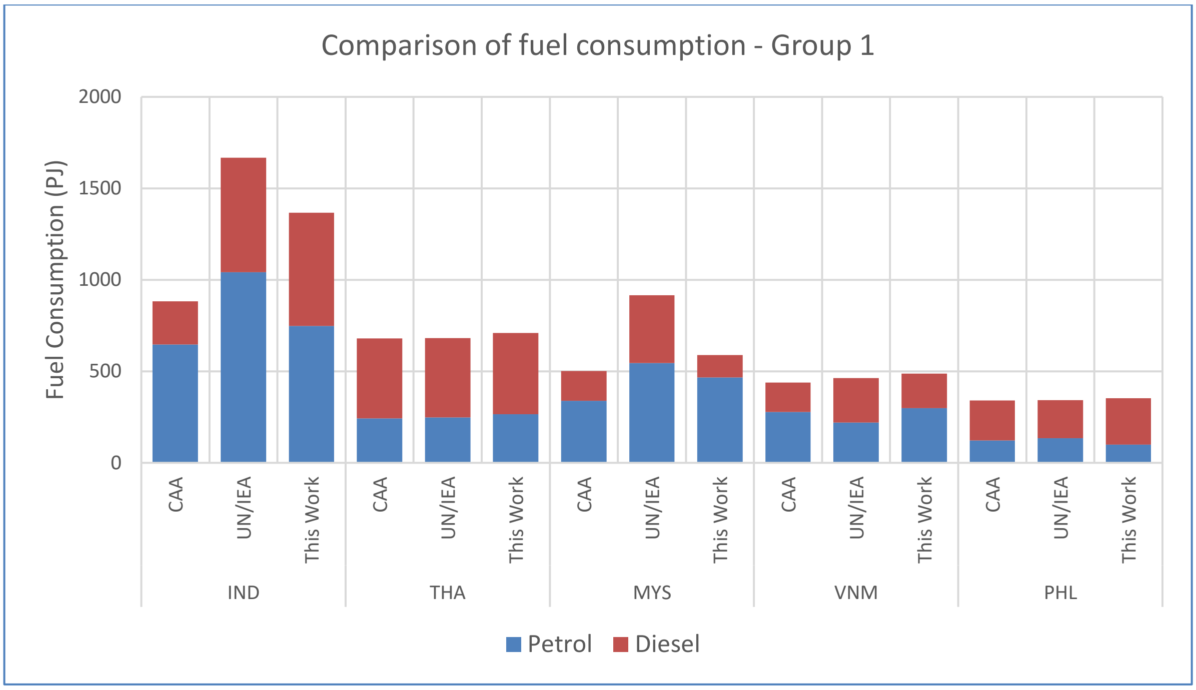

Figure 3.20: National fuel consumption evaluated by different models – group 1

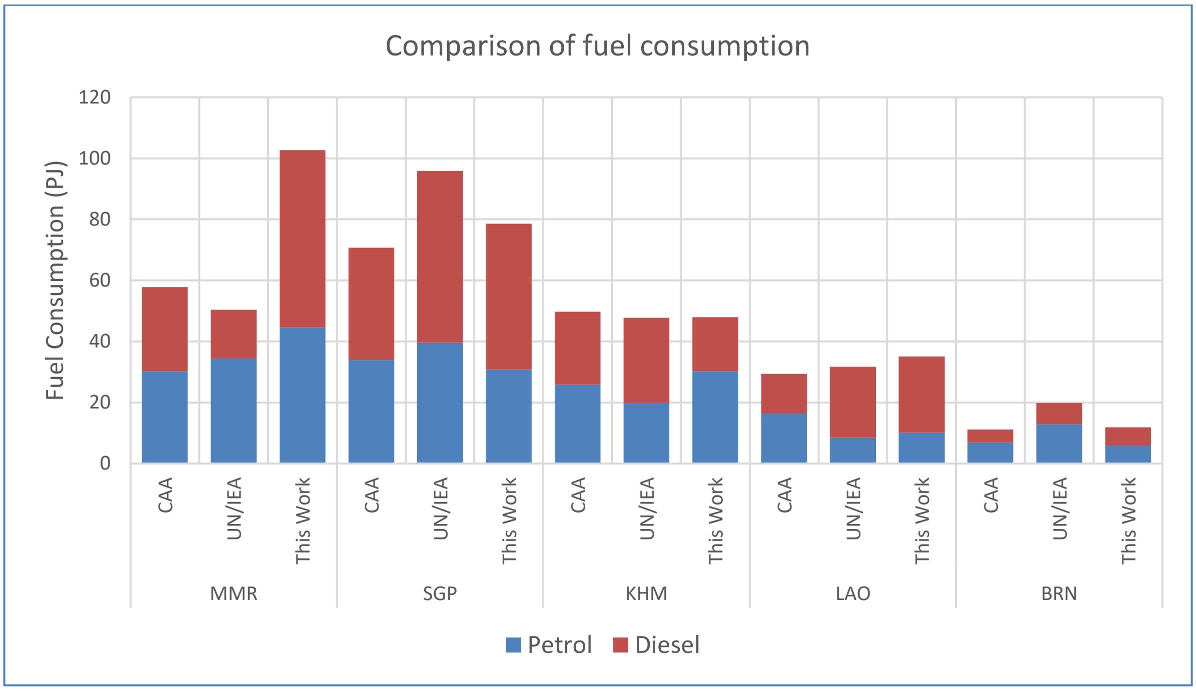

Figure 3.21: National fuel consumption evaluated by different models – group 2

It is observed from Figure 3.20 and Figure 3.21 that for majority of the countries, viz. Thailand, Vietnam, Philippines, Singapore, Cambodia and Laos, the results from the model seems to be in good agreement with literature. The ratio between petrol and diesel consumption is also within agreeable range. Even though the fuel consumption estimated by our model for Indonesia, Malaysia and Brunei are not the same as the ones in literature, it still is within the close range. However, in case of Myanmar, the prediction from the model seems to be on the higher side. The variation could be because CAA made their study in 2011 using a forecasting tool for evaluating the 2014 scenario, whereas this work is based on real data from literature. Due to forecasting, a variation in fleet size is found.

It is to be noted that, there were iterations carried out (with the parameters that were assumed being varied) to arrive at the most suitable and realistic model. Hence, it can be said with good certainty that the model developed here is very close to the actual case. In addition to that, the CAA study uses a single emission/fuel consumption value for each vehicle type. Whereas in this study, each vehicle type is further classified by its size and emission standards and their corresponding emission factors are used. Because of the use of real data, classification of vehicles at finer resolution and tuning of the assumptions made through iteration, a model closer to reality is arrived at, which improves the existing literature. This validated model can predict the emission of GHGs and pollutants at a greater accuracy. The vehicle fleet distribution of all the countries (like Singapore in Table 3.7) can be found in the appendix (Table A.1 to Table A.9).

4 Bio-energy availability in ASEAN

In order to evaluate the amount of the annual fossil fuel demand that can be replaced by energy derived from biomass residues, the type and total amount of biomass residues available in ASEAN needs to be quantified and the energy products that are producible from them needs to be identified. In addition to that, for enabling the evaluation of biomass transport distance and the relationship it has with the size of the power plant, the location of the residue availability needs to be identified. The aim of this chapter is to determine the major biomass residue types available in ASEAN, quantify them and identify their location. The carbon neutrality of the biomass resources is discussed briefly. The different energy products that can be produced from the available residues and their production pathways of are identified as well.

The biomass residue potential evaluation was published as an article titled "Techno-economic estimation of power generation potential from biomass residues in Southeast Asia" in a peer reviewed journal 'Energy' and has been well received by the scientific community [113]. While the article focussed on cost estimation of electricity generation from biomass residues in ASEAN, this chapter will restrict itself only to quantification of the residues and identification of their locations.

4.1 An overview of agriculture in ASEAN

As seen from chapter 2, agriculture plays a major role in the economy of ASEAN nations. About 30.4% of ASEANs land area is utilised for agricultural activities alone. Rice, sugarcane and oil palm are the major agricultural products of ASEAN. ASEANs agriculture sector has been experiencing steady growth in the recent past. The area of land under agriculture has grown by 22% from 1990 to 2015. In the same time period, the production of rice and sugarcane almost doubled, while that of palm oil grew by six folds. This indicates a vast improvement in the productivity of the agriculture sector. Figure 4.1 shows the crop production of the major crops in ASEAN between 1990 and 2015 [114].

Figure 4.2 shows the individual contribution of each country towards rice production [114]. In general, Indonesia, Thailand, Vietnam and Myanmar are the major contributors of agricultural produce. Brunei and Singapore, being developed industrial nations with small land area, do not produce a large quantity of agricultural products.

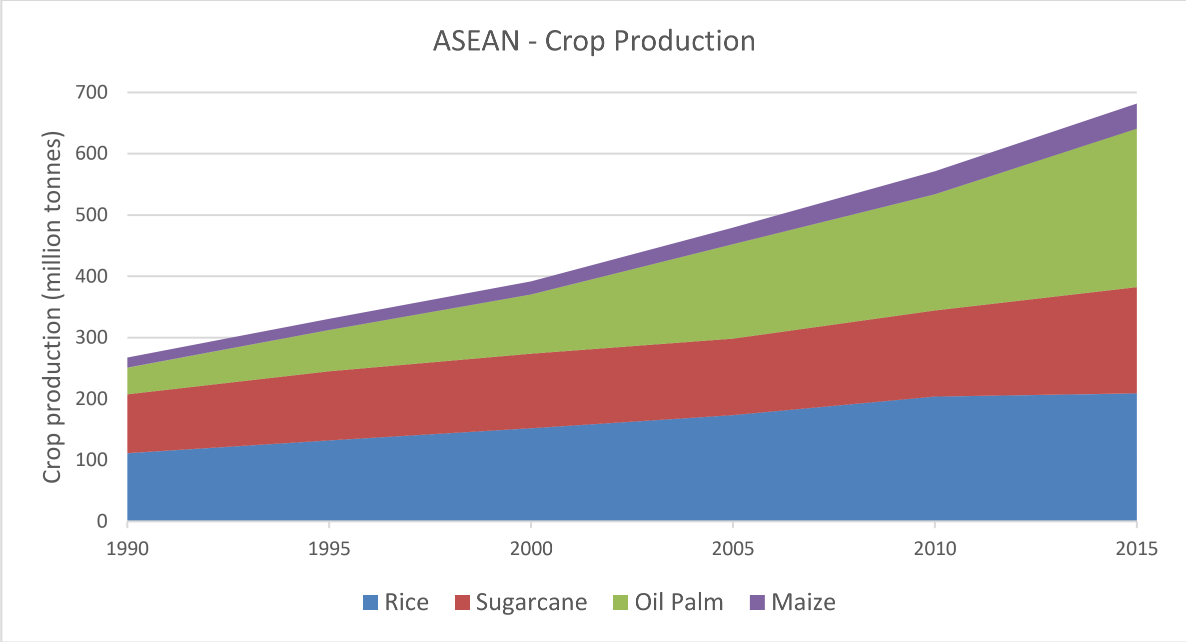

Figure 4.1: Crop production in ASEAN between 1990 and 2015

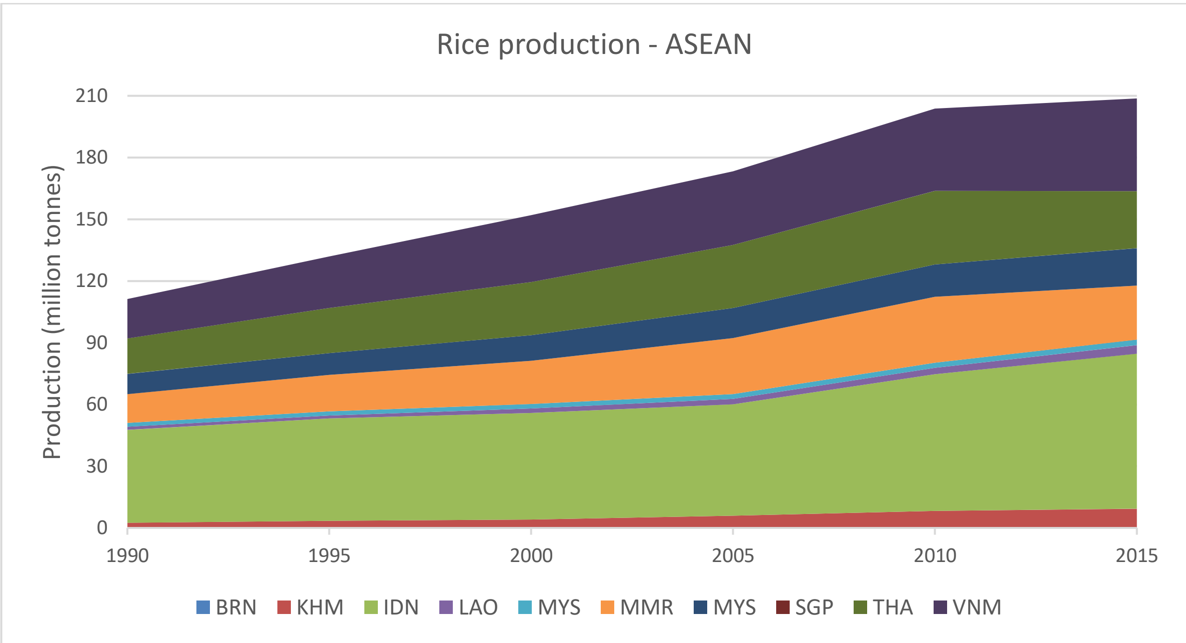

Figure 4.2: Rice production in different ASEAN nations between 1990 and 2015

As the ASEAN countries are in the tropical region, it is characterised by large and dense forest cover and can produce biomass round the year. Around 49% of its land area is covered with forest, which is higher than the global average of 31%. It also contributes to 5.2% of the entire global forest cover. Apart from playing the major role of maintaining the region's environment, ASEAN's forest has been the main source of timber and other forest products. The residents use the energy in the woody biomass from forests as a domestic fuel. The wood from forest is also used as a raw material for the production of lumber products such as furniture, plywood, paper pulp, etc [115]. Forests are the main source of Industrial Roundwood production as well. Beyond local use, ASEAN also exports timber and other forest products.

Livestock rearing is an important activity in ASEAN. This region is home to 2.6 billion chickens, 47 million head of cattle, 71 million head of pigs, 26 million head of sheep, 15 million head of buffalo and 12 million head of goats. Foods of animal origin (milk, egg and meat) are a good source of protein and hence their demand is on the increase. ASEAN countries not only produce meat for local consumption but also exports them [116].

The production of agricultural products is accompanied by the production of residues as well. For example, production of rice also produces rice straw and rice husk. Similarly, sugarcane produces sugarcane leaves and top and bagasse as well. Some amount of residue is ploughed back into the soil. A certain quantity is also used for material and energy purposes. The rest of the biomass is either dumped in landfills or burnt openly in the fields [117]–[120]. Similarly, production of forest products produces logging residues, which are normally left on forest floors. All these residues are high in lignocellulosic content (further discussed in section 4.6.1). Likewise, livestock produces manure, which can be digested to produce biogas, which can subsequently be converted into other energy products. The anaerobic decay of biomass produces methane which is 25 times more potent as a GHG as compared to CO_2. Open field burning produces ash and soot which causes health hazards [121], [122]. Hence by utilising the energy from these residues, one can replace part of fossil fuel demand and counter the issue of waste pileup.

4.2 Literature survey on bio-energy studies in ASEAN

There are a few studies that estimate the potential of Biomass in ASEAN countries. In their work titled 'Biofuel potential in Southeast Asia: Raising food yields, reducing food waste and utilising residues', the International Renewable Energy Agency (IRENA) estimated the biomass resource potential in Indonesia, Malaysia, Philippines, Thailand and Vietnam [123]. Carlos et al, characterised the biomass energy projects in Southeast Asia [124]. Sasaki et al., evaluated the woody biomass potential in Southeast Asia, between 1990 and 2020, focusing on issues such as forest degradation and deforestation [47]. There have also been a few country/crops specific work that have been done on energy potential of biomass residues. Yano et al., calculated the ethanol production potential from oil palm empty fruit bunches (EFB) in Indonesia, Malaysia and Thailand [125]. They estimate that about 2% of gasoline consumption can be replaced in Indonesia and Malaysia with ethanol produced from Oil Palm EFB alone (under moderate availability assumption). They concluded that the palm oil producing Southeast Asian nations, can produce large quantities of second generation bio-ethanol. Shafie et al., estimated the energy generation based on biomass residues in Malaysia [118]. They estimate the electricity generation potential and its cost of production from various crop residues such as rice husk, rice straw, sugarcane bagasse, etc. Similarly, Goh et al., estimated the second generation bio-ethanol production potential from lignocellulosic residues in Malaysia [126]. The potential of biomass residue availability in Thailand was estimated by Bhattacharya et al [127]. Prasertsan and Sajjakulnukit presented the biomass and biogas energy situation in Thailand in 2005 [128]. In a more recent work, Sajjakulnukit et al., estimated the non-plantation biomass resources in Thailand, which include agricultural residues, animal manure, municipal solid waste (MSW), among others [129]. A similar study was carried out for Philippines by Elauria et al. [130] , and for selected Asian countries by Bhattacharya et al [131]. Abe et al. explored the possibility of electrifying villages of Cambodia with gasification of agricultural residues such as rice husk, cashew nut shells, etc [132]. Most of the studies mentioned above calculate the biomass availability at national level. They do not focus on the distribution of biomass across the landscape of the country. Krukanont and Prasertsan predicted the geographical distribution of biomass and potential sites of rubber wood fired power plant in Southern Thailand [133]. A similar approach was followed by Jenjariyakosoln et al, in their study on the energy and GHG emission reduction potential of sugarcane field residues power generation in Thailand [134]. However, these studies are restricted to smaller regions or at the maximum, one country. Similar studies for other ASEAN countries are not found either. There are a few GIS based studies such as [135], [136] which focuses on analysing the logistics cost, optimal location and sizing of power plants. But these do not estimate the availability potential.

Detailed studies on all crops for all the countries are not available in the literature. Most of the work focuses on rice, sugarcane and palm oil residues only. While Malaysia and Thailand have many detailed studies on them, countries like Philippines, Cambodia, Vietnam and even Indonesia (the highest producer of agricultural products) have not been explored at great depths. Also, the assumptions, data sources and methodology adopted in the different studies (that were focussed on one nation or region) are varying. This makes the comparison of the results between the studies difficult. Also, most of the studies focus on estimation of biomass potential at national level, and do not identify the location of the biomass residues. Thus, there is a need to develop a uniform methodology, spanning across the different nations for the Thesis. The location of the biomass residues for evaluating the transportation distances in the later chapters also needs to be identified. The main crux of this chapter is focussed on these aspects.

4.3 Proposed methodology

The primary focus of this thesis lies with second generation bio-energy. In other words, only energy from, biomass residues are being dealt with (and not energy crops). The evaluation of energy from biomass residues at national level generally deal with the following residue types:

1. Agricultural residues
2. Animal manure
3. Forest residues
4. MSW

Agriculture crops	Forestry	Livestock
• Rice • Maize • Sugarcane • Oil Palm • Cassava • Coconut • Coffee • Groundnut	• Industrial Roundwood coniferous • Industrial Roundwood non-coniferous	• Cattle • Buffalo • Sheep • Goat • Poultry • Pig

Figure 4.3: The various categories and sources of biomass residues considered in the study

While it is possible to develop a common methodology for the first three residue types, it is not possible to do the same for MSW. They need to be dealt with on a case by case basis. The composition, derivable energy and the collection & treatment method of MSW varies a lot between the countries and even cities. Also, as seen from a few examples, they form a very small portion of the total residue availability [129]–[131], [137]. Hence, it is omitted in this evaluation. Based on the main biomass types that grow in Southeast Asia, the primary crops, forest products and livestock type that are of interest for this thesis are tabulated in Figure 4.3.

The general methodology followed is to first quantify the production of each kind of crop/livestock on an annual basis. Then the relationship between biomass production and residue production (also known as residue production ratio (RPR)), is established. RPR is discussed in detail in section 4.3.2. Since these residues are used for other purposes (process heat, ploughing back into the field, etc.), an availability factor (AF) is introduced. The product of biomass production, RPR and AF gives the total quantity of residue that are available for energy purposes. For the ease of representation, the mass of residues is converted into energy using their lower heating value (LHV). Then, based on the land use patterns and region of production of these crops/forestry/livestock, the location of these biomass residues is identified. The outcome of this exercise would be a map containing the location and quantity of each biomass residue type, for the entire ASEAN. The biomass availability is broken down into three sections.

4.3.1 Quantification of the crop, forestry and livestock production

For deriving the geo-spatial grids of biomass production, the most recent production data of various biomass sources is taken from the literature. The reference year is taken to be 2013, as the data for 2014 was not available for all the countries. As discussed before, it is decided to identify the location of biomass. Hence, instead of procuring the production data at national level, an effort was made to procure it as province or district level. This increases the accuracy of location prediction. However, if data at a finer resolution (i.e. province/district level) was not available, then the national level data provided by Food and Agricultural Organisation Corporate Statistical Database (FAOSTAT) is used [114]. In a few cases, the regional level (i.e., province/district level) data was available for a year other than 2013 (for example 2010). In such cases, it was adjusted to 2013, by normalising it with the annual growth rate of the crops at national level, which is derived from FAOSTAT. Table 4.1, found in next page, shows the number of regions at which data was collected for each country for each biomass type. The fineness/coarseness of these areas is found as an example in the map shown in Figure 4.4.

The country agricultural statistics data websites were analysed for assimilating the agricultural crops production data. The data on agricultural biomass was collected for 830 different administrative regions in ASEAN. The major reference source used for the collection of these data are [114], [138]–[145]. Good quality data on agricultural produce is available for most countries under consideration. Apart from the city state of Singapore, the highest resolution of data is available for Indonesia (at 3,675 sq km per administrative region). The lowest resolution of data is found for Malaysia (at 23,468 sq km per administrative region). However, this coarseness in data shall be accounted for, by utilising data on land use patterns, which is explained in section 4.3.3. Oil Palm production refers to production of fresh fruit bunches (FFB). For the evaluation of forestry biomass, no consistent data at high spatial resolution is available. Country wide annual production volume of industrial round woods is taken for the year 2013 from FAOSTAT [114]. The livestock production data is collected for 754 regions in

ASEAN. The regional resolution of biomass data for livestock is provided in Table 4.1. The livestock data represents the number of animals in each region. It is a large database that has been obtained from various sources [114], [138], [139], [146]–[149]. Acquisition of raw data forms the main input of the available energy estimation, and hence a great effort is made in this front.

Biomass Type	BRN	KHM	IDN	LAO	MYS	MMR	PHL	SGP	THA	VNM
Rice	1	24	493	17	14	63	79	1	77	61
Maize	1	24	493	17	14	63	79	1	77	61
Sugarcane	1	24	493	17	14	63	79	1	77	61
Oil Palm	1	1	493	1	14	63	79	1	77	1
Coconut	1	24	493	17	14	63	79	1	77	61
Groundnut	1	24	1	17	14	63	79	1	1	1
Cassava	1	24	493	17	14	1	79	1	77	61
Coffee	1	1	493	1	14	63	79	1	77	1
Forestry	1	1	1	1	1	1	1	1	1	1
Cattle	1	1	497	18	13	1	82	1	77	63
Buffalo	1	1	497	18	13	1	82	1	77	63
Sheep	1	1	497	1	13	1	1	1	1	1
Goat	1	1	497	18	13	1	82	1	1	1
Poultry	1	1	497	18	13	1	1	1	77	63
Pig	1	1	497	18	13	1	82	1	77	63

Table 4.1: Number of regions for which biomass production data are collected

The national country level data of biomass production in ASEAN is shown in Table 4.2. Though the data at finer resolution (smaller administrative areas) for all the biomass types is available, representing all of them in the written thesis is an impossible task. Hence, as a representative of the data, a geo-spatial map of rice production in ASEAN is presented in Figure 4.4. The map shows the administrative regions for which the data has been collected, with a darker green representing higher rice production.

Biomass group	Biomass Type	BRN	KHM	IDN	LAO	MYS	MMR	PHL	SGP	THA	VNM
Agricultural crops *(1000 tonnes)*	**Oil Palm - FFB**	0.0	0.0	120000.0	0.0	95728.6	0.0	473.4	0.0	12812.0	0.0
	Rice	1.9	9390.0	71279.7	3415.0	2626.9	28767.0	18439.4	0.0	36062.6	44039.3
	Maize	0.0	927.0	18511.9	1150.0	87.8	1700.0	7377.1	0.0	5062.8	5190.9
	Sugarcane	0.0	600.0	33700.0	1180.0	214.0	9650.0	31874.0	0.0	100096.0	20131.1
	Cassava	3.0	8000.0	23936.9	1120.0	81.7	630.0	2360.5	0.0	30228.0	9757.7
	Groundnut	0.0	30.0	1340.0	48.0	0.6	1375.0	29.1	0.0	47.0	492.0
	Coffee	0.0	0.4	698.9	89.0	16.6	8.3	78.4	0.0	50.0	1461.0
	Coconut	0.0	58.0	18300.0	0.0	646.9	425.0	15353.2	0.2	1010.0	1303.8
Industrial roundwood *(1000 m^3)*	**Coniferous**	0.0	7.0	205.5	0.0	187.0	0.0	0.0	0.0	0.0	350
	Non-coniferous	107.3	135	62400	855	17636	5078	3858	0	14600	6450
Livestock *(million animals)*	**Cattle**	0.0	2.9	16.6	1.7	0.8	14.7	2.5	0.0	5.1	5.2
	Buffalo	0.0	0.7	1.5	1.2	0.1	3.3	2.9	0.0	1.2	2.6
	Pig	0.0	2.2	8.2	2.3	1.7	10.5	11.8	0.3	7.9	26.3
	Poultry	19.2	21.3	1844.0	33.5	311.0	206.1	173.5	4.3	287.0	314.7
	Goat	0.0	0.0	18.6	0.5	0.5	3.9	3.7	0.0	0.5	1.4
	Sheep	0.0	0.0	14.6	0.0	0.1	0.9	0.0	0.0	0.1	0.0

Table 4.2: Biomass production in ASEAN

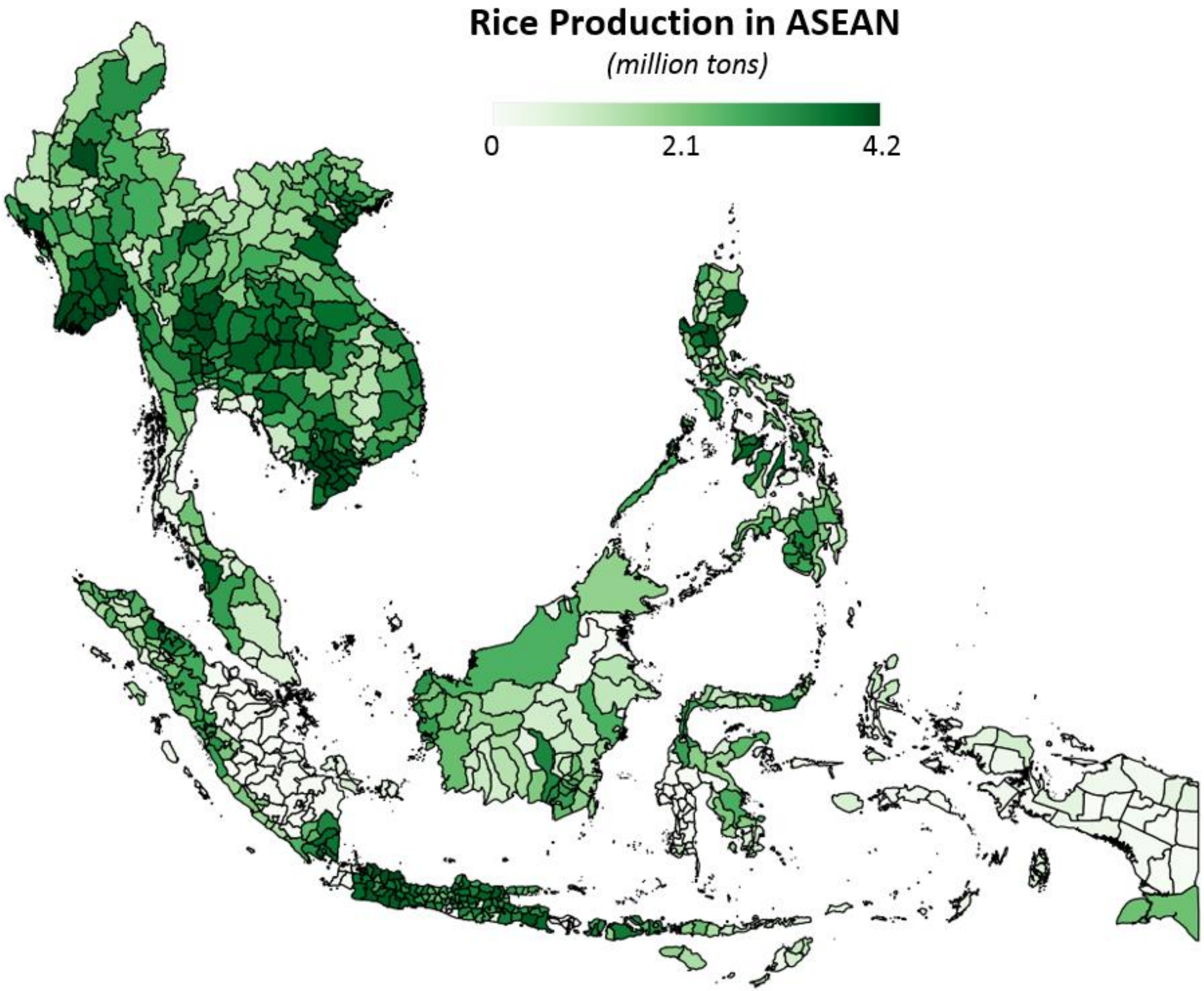

Figure 4.4: Rice Production in ASEAN, shown at a finer resolution

4.3.2 Estimation of residue availability

The general idea is to quantify the amount of residue produced per unit production of the biomass. However, the technique varies between the three types of residues under consideration, which is explained below.

4.3.2.1 Agricultural residues

Production of crops generate residues such as such as rice straw, rice husk, etc. They can be classified into field-based residues and process-based residues. The ones that are produced on the field, during the process of harvesting, are called field-based residues (e.g., rice straw, sugarcane tops and leaves (trash), etc). There are some secondary uses to them like being used for animal feed, ploughing back into soil for retaining soil texture, etc. These are tough to be collected and as mentioned before, are normally left over on the field or burnt in open air. Hence a large portion of it is available to be used for energy purposes. The other group of agricultural residues are known as process-based residues. These are the residues that occur during processing of the crops. Example of these types of residues would be rice husk and sugarcane bagasse. As these are generated from the already collected crops, they have a higher use percentage. They are mainly used for producing process heat/electricity at the crop processing plant. Hence, a lower quantity of these residues is available for energy purposes. The different agricultural residues considered in this study are tabulated in Table 4.3.

For evaluating the energy available from agricultural residues, 3 different variables for each crop residue needs to be evaluated, viz. RPR, AF and LHV. RPR defies the unit quantity of waste per unit quantity of agricultural produce. For example, processing 1 kg of rice produces approximately 0.23 kg of rice husk. There are multiple sources for RPR for different crops that are available in the literature. Figure 4.5 plots the RPRs for rice straw and rice husk, that have been procured from different sources [129], [150]–[153]. While the variation between RPRs for process-based residues is small, there seems to be a large variation in the RPRs of the field-based residues. There are multiple reasons for the same. The definition of what a residue is, the moisture content of the residue (as RPR is defined as kg residue/kg crop), the variety of the crop (i.e., different kind of rice), etc. After carefully inspecting the different sources and, considering the mean value from different sources, a single value for each residue type is taken from literature and tabulated in Table 4.3. Such a detailed analysis of the RPRs is necessary as its value has a huge impact on the estimation of available energy.

For converting the quantity of residues into available energy, the LHV values are used. The LHV values are closely related to RPR values (as they can be evaluated for different moisture contents). Hence, careful considerations were made to match the LHV values with the chosen RPR values. LHV values are tabulated in Table 4.3. The residue availability has been taken from literature. Their sources and values are tabulated in Table 4.3.

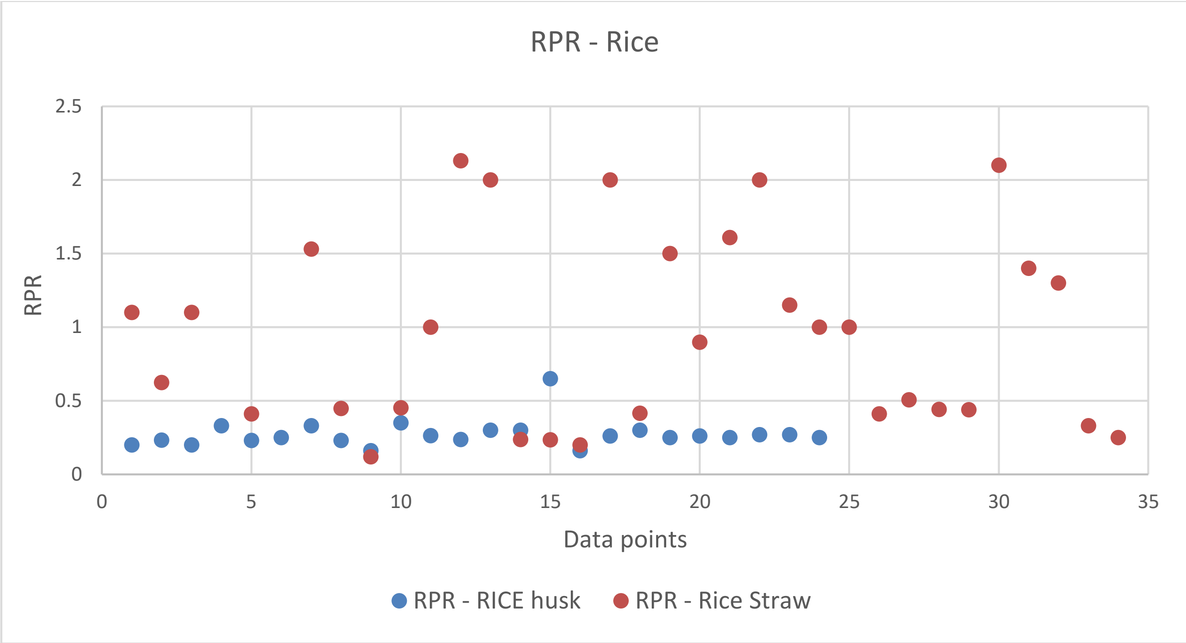

Figure 4.5: The RPA values for rice straw and rice husk acquired from different sources

Oil Palm residues follow a slightly different methodology than the others. Some RPR values found in the literature are based on 'per tonne of crude palm oil (CPO)' while the others are based on 'per tonne of FFB'. To normalise all the values to FFB, a correlation of 0.2079 kg CPO/kg FFB is taken [154]. While most oil palm residues (viz. empty fruit bunches (EFB), shell, fibre and frond) are solid, palm oil mill effluent (POME) a process residue that is produced during the processing of FFB to CPO, is a liquid. POME produces methane which can be used for energy purposes. Hence the LHV value of POME is evaluated based on a methane production capacity of 12.36 kg CH_4/tonne of POME and an LHV value of methane at 50 MJ/kg [154].

4.3.2.2 Forest residues

The logging of wood from forests produce logging residues which are mostly left on the forest floors. These residues are high in their lignocellulosic content and hence are highly suited for energy production. The RPR of for forest residues (i.e., logging residues) found in literature have the unit kg logging residue per kg wood produced. Whereas the roundwood production values procured from literature (as discussed in section 4.3.1) is given in m^3. Hence, the production volume needs to be converted into mass, which is done using the density value of 0.75 tonnes/m^3 for coniferous wood and 0.85 tonnes/m^3 for non-coniferous wood [113]. These residues can be equated with field based agricultural residues. In general, most of the process-based residue (sawdust, shavings, etc.) is already used for energy and material purposes and hence is not considered in this thesis. The LHV and AF values for the forest residue are taken from literature and tabulated in Table 4.3.

4.3.2.3 Livestock residues

Livestock are mainly reared to produce meat and milk, and sometimes wool. However, they also produce manure, which is of liquid/semi solid nature. The liquid nature of animal manure is primarily suited for anaerobic digestion which produces methane (which can be converted into other energy product in the subsequent steps). Hence, the method followed for livestock is slightly different from that of agriculture and forest residues. The RPR here denotes the total volatile solids (VS) produced per animal head. The LHV value here denotes the product of the respective methane production per tonne of VS of each animal (taken from [155]) and the energy density of methane. The availability factors are also taken from the same source as above.

Biomass Group	Biomass Type *'x'*	Biomass Residue *'b'*	RPR *(kg/input)*$^{\alpha}$	LHV *(MWh/tonne)*$^{\beta}$	AF *(-)*	Source
Agriculture	Rice	Straw	1.00	3.89	0.50	[152], [156]
	Rice	Husk	0.23	3.57	0.47	[129], [152]
	Maize	Stalk	1.00	3.97	0.33$^{\gamma}$	[157], [158]
	Maize	Cob	0.25	4.62	0.67	[129]
	Sugarcane	Bagasse	0.25	1.79	0.21	[129]
	Sugarcane	Top & Leave	0.30	1.89	0.99	[129]
	Oil Palm	Shell	0.07	4.72	0.04	[129], [159]
	Oil Palm	Fibre	0.13	3.08	0.13	[129], [159]
	Oil Palm	EFB	0.23	1.69	0.58	[129], [159]
	Oil Palm	POME	0.67	0.17	0.65	[159], [160]
	Oil Palm	Frond	0.55	2.21	0.05	[129], [159], [160]
	Cassava	Stalk	0.09	4.72	0.41	[129]
	Coconut	Husk	0.36	4.09	0.60	[129]
	Coconut	Shell	0.16	4.58	0.38	[129]
	Coconut	Frond	0.23	4.04	0.81	[129]
	Coffee	Husk	21.00	3.44	0.33$^{\gamma}$	[158]
	Groundnut	Shell	0.32	3.12	1.00	[129]
	Groundnut	Straw	2.30	4.88	0.33$^{\gamma}$	[158], [161]
Forestry	Industrial Roundwood coniferous	Logging Residues	0.67	4.31	0.40	[162], [163]
	Industrial Roundwood non-coniferous	Logging Residues	0.67	4.31	0.40	[162], [163]
Livestock	Cattle	Manure	0.84	1.01	0.02	[155]
	Buffalo	Manure	1.42	1.01	0.05	[155]
	Sheep	Manure	0.12	1.31	0.02	[155]
	Goat	Manure	0.13	1.31	0.02	[155]
	Poultry	Manure	0.007	2.43	0.47	[155]
	Pig	Manure	0.11	2.93	0.47	[155]

$^{\alpha}$ RPR for agriculture and forestry residue represent unit mass of residue produced per unit mass of biomass product and RPR for livestock represents tonne of residue produced per animal.

$^{\beta}$ LHV for agriculture and forestry residue is expressed as MWh/tonne of residue and LHV for livestock is expressed as MWh/tonne of VS.

$^{\gamma}$ These numbers are assumed values.

Table 4.3: Considered biomass residues and their RPR, LHV and AF values

The annual energy available '*a*' from residue type '*b*' at each administrative region '*c*' is given by eq. 4.1,

$$a_{cb} = BP_{xc} \cdot RPR_b \cdot LHV_b \cdot AF_b \qquad \text{(eq. 4.1)}$$

, where BP_{xc} is the production of biomass type '*x*' in each administrative region '*c*', RPR_b, LHV_b, AF_b is the residue production ratio, lower heating value and availability factor of residue type '*b*'. The energy available at national level for each country '*n*' and biomass type '*b*' is given by eq. 4.2,

$$a_{nb} = \sum_{c \in Z_n} a_{cb} \quad \text{(eq. 4.2)}$$

, where Z_n represents the set of all administrative regions within country the '*n*'.

Based on the methodology mentioned above, the energy available from biomass residues is evaluated. Figure 4.6, represents the total accumulated energy at national level for each ASEAN nation. Indonesia (413 TWh), Thailand (195 TWh) and Vietnam (155 TWh) are the largest producers of biomass residues in ASEAN. Brunei (0.27 TWh) and Singapore (0.077 TWh) are on the other end of the spectrum, producing very low quantity of biomass residue energy annually. Agricultural residues contribute to 86% of the biomass residues energy and the next big contribution comes from logging residues at 10%. The livestock contributes to a mere 4%. Table A.10 in the appendix, shows the energy available from of different biomass residue types in different countries.

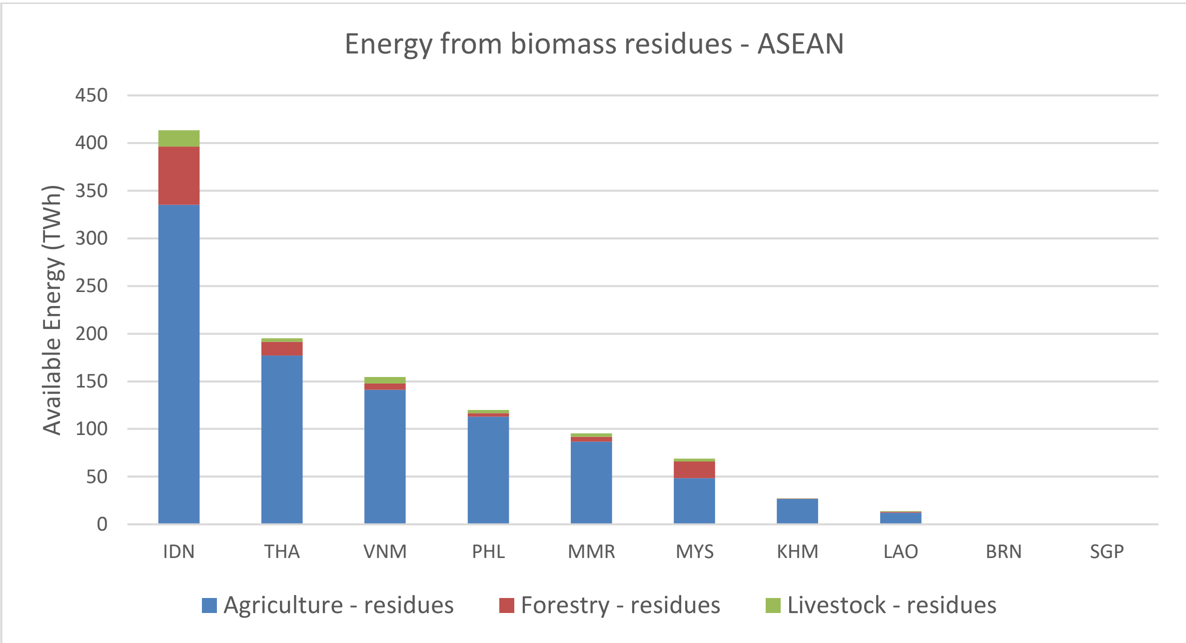

Figure 4.6: Energy from biomass residues in different ASEAN countries

4.3.3 Identifying the location of the available biomass residues

One of the big issues associated with energy recovery from its biomass is its transportation. In general, biomass (in its unprocessed form) is associated with lower energy densities and larger collection areas. The collection area/collection radius also largely depends on the installed capacity of the powerplant. Larger powerplants require bigger collection areas. Hence it becomes necessary to identify the location and distribution patterns of biomass residues of each country. Primarily, this is done by distributing the biomass residue to the land type it corresponds to. By performing this exercise, the issue associated with coarseness of the biomass production data collection is nullified.

4.3.3.1 Land use data:

For agricultural residues, the land use data is collected from [164]. It is a raster grid with a cell size of 15 arc seconds, which approximately corresponds to 450 m length at equator. The land use types that are associated with agriculture are 'croplands' and 'croplands/natural vegetation mosaic', which correspond do land use type 12 and 14 in ref [164]. It is assumed that the dedicated 'croplands' have twice as much production as the cells that are indicated as 'cropland/natural vegetation mosaic'. The same data source and cell size are used for assessing forestry biomass. Any type of forest mentioned as the major land use type is chosen for this purpose (land use type 1,2,3,4, and 5 in ref. [164]. However, the raster cells which are indicated as protected area in reference [165] are the forest areas that are untouched by humans. Hence, they are ignored when considering the distribution of forestry biomass. For livestock, the distribution is done based on the livestock grid model presented in [166]. The grid resolution available here is 30 arc seconds. The accumulated energy map is shown in Figure 4.8 which shows the energy available from all the biomass residues at each pixel as a raster grid. The major observation seen from the map is that, highest density of energy from biomass residues is available close to highly populated areas on Java, around Hanoi, Ho Chi Minh, Bangkok, Yangon, Manila and the east coast of Peninsular Malaysia. The other important observation is that, high biomass energy densities can be found along the major rivers, viz. Mekong, Irrawaddy, Red River, Chao Pharaya, etc.

4.3.3.2 Converting Raster back into Vector

The main idea of collecting data at the level of a province and not country is to identify the location of biomass at a higher accuracy. To identify the location of biomass at higher precision, rasterised land use data is used. The reason for identification of location of residues is two folds. Firstly, for this thesis work, the transport distance of biomass and its relationship with the size of a powerplant needs to me estimated. This shall be further dealt with in 5.1.2.2 of chapter 5. Secondly, this data was also utilised for cost estimation of power generation from biomass residues in ASEAN. This is well documented in the publication titled "Techno-economic estimation of power generation potential from biomass residues in Southeast Asia" [113]. The main idea here as well was to identify the transportation distances. While working with GIS tools, it is easier to work with vectors. Hence, there is a need to convert the raster layer back into vector. This is done by applying a vector layer of higher fineness (i.e., smaller administrative regions) and summing all the raster cells that are found within the layer. This is explained in the eq 4.3,

$$a_{fb} = \sum_{p \in Z_f} a_{pb} \qquad \text{(eq. 4.3)}$$

, where a_{fb} annual energy available from biomass residue type '*b*' at the finer administrative region '*f*', a_{pb} is annual energy available from biomass residue type '*b*' at each pixel '*p*' and Z_f corresponds to set of all pixels contained within administrative region '*f*'. This is explained graphically in Figure 4.7, where it is shown how rice production data that was collected at a coarser resolution for Thailand, has been converted into a finer resolution using land use data. Table 4.4 provides the number of model regions for each country at finer and coarser resolution. The data for accumulated energy for entire ASEAN at fine resolution is shown in Figure 4.9.

	No. of model regions	
	Coarse	**Fine**
BRN	1	33
KHM	24	184
IDN	497	887
LAO	18	141
MYS	14	183
MMR	63	339
PHL	82	234
SIN	1	9
THA	77	948
VNM	63	967

Table 4.4: Number of model regions at coarse and fine resolution

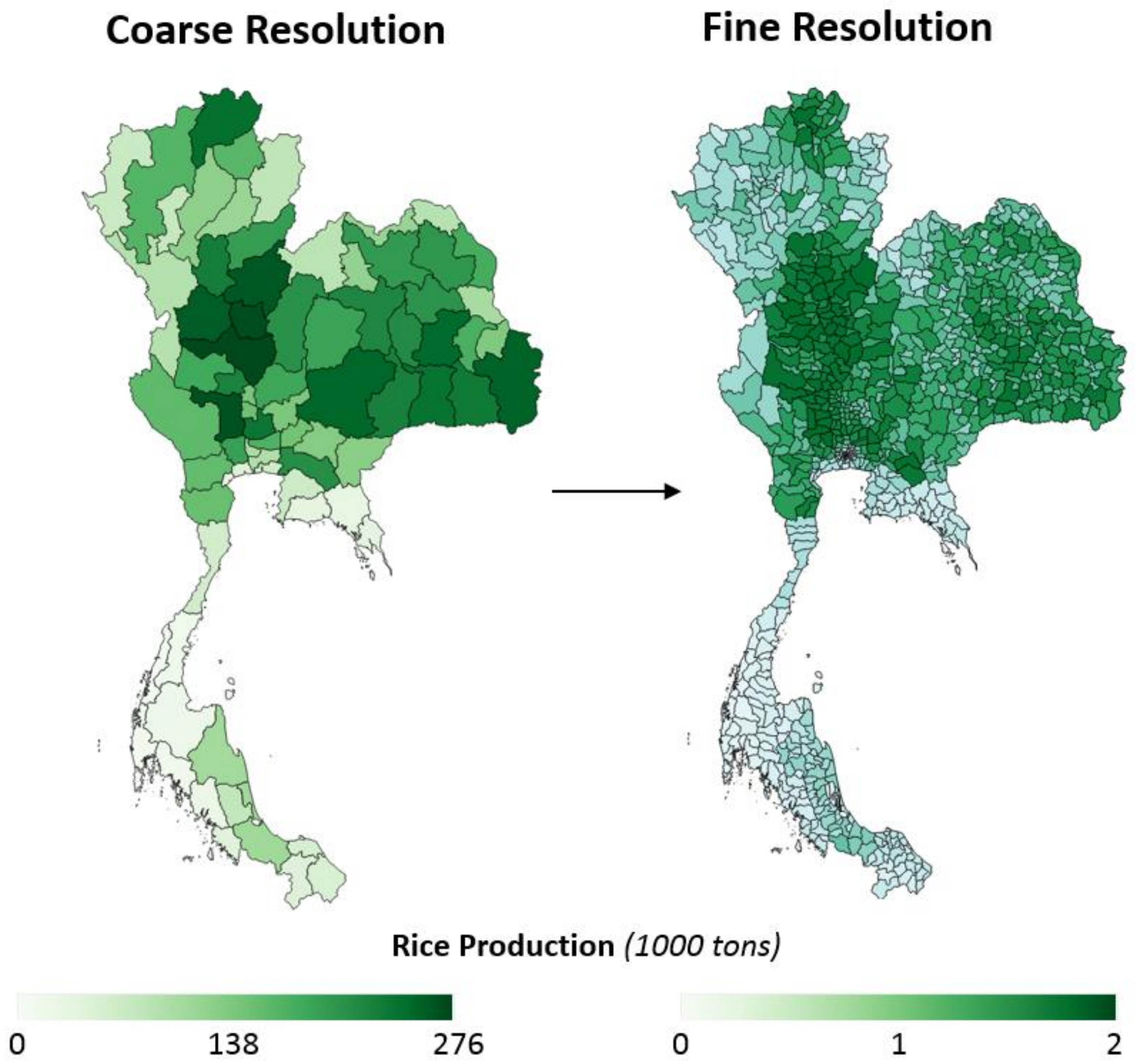

Figure 4.7: Rice production data for Thailand and Coarse and Fine resolution

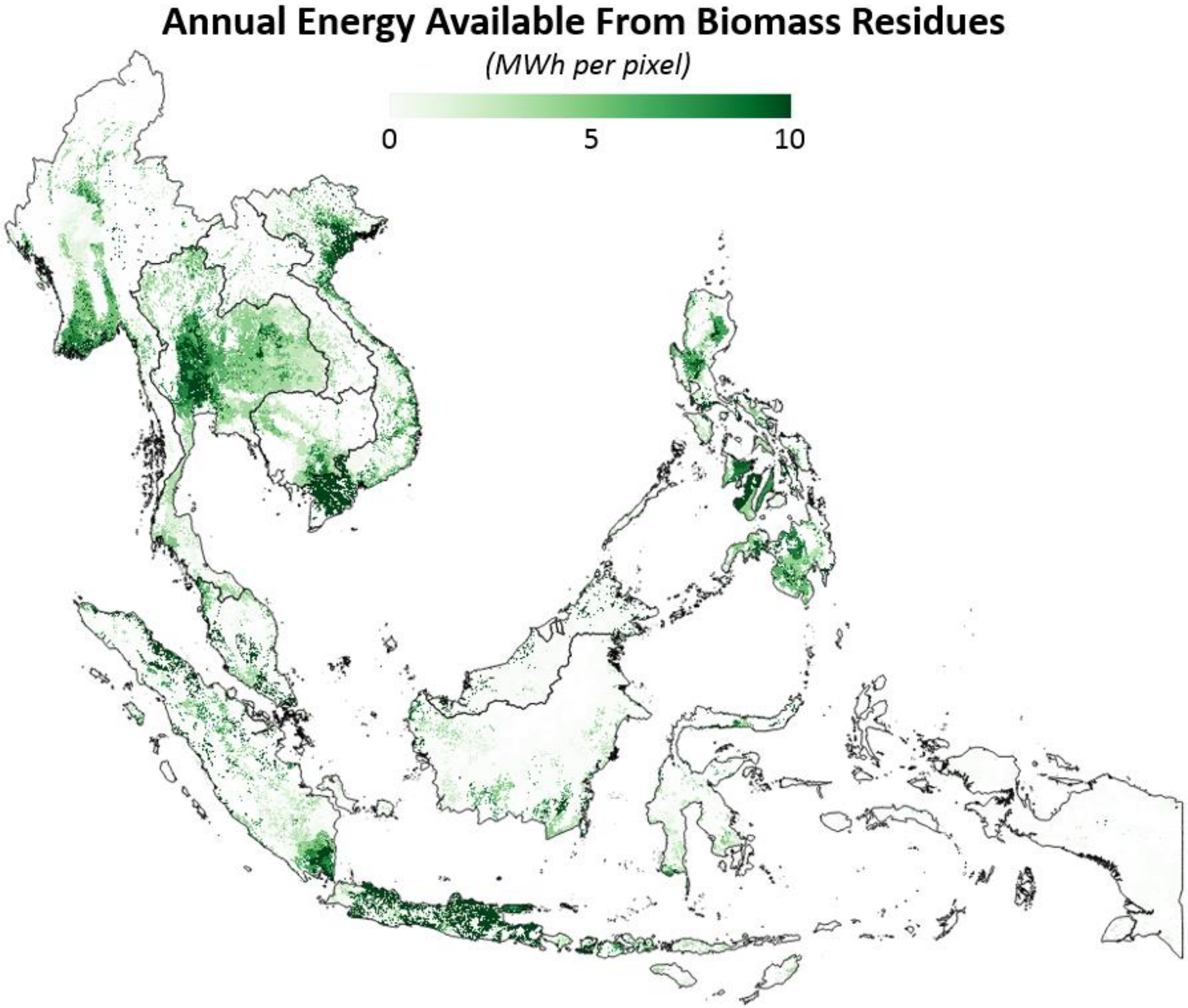

Figure 4.8: Raster grid of energy available from all biomass residues in ASEAN

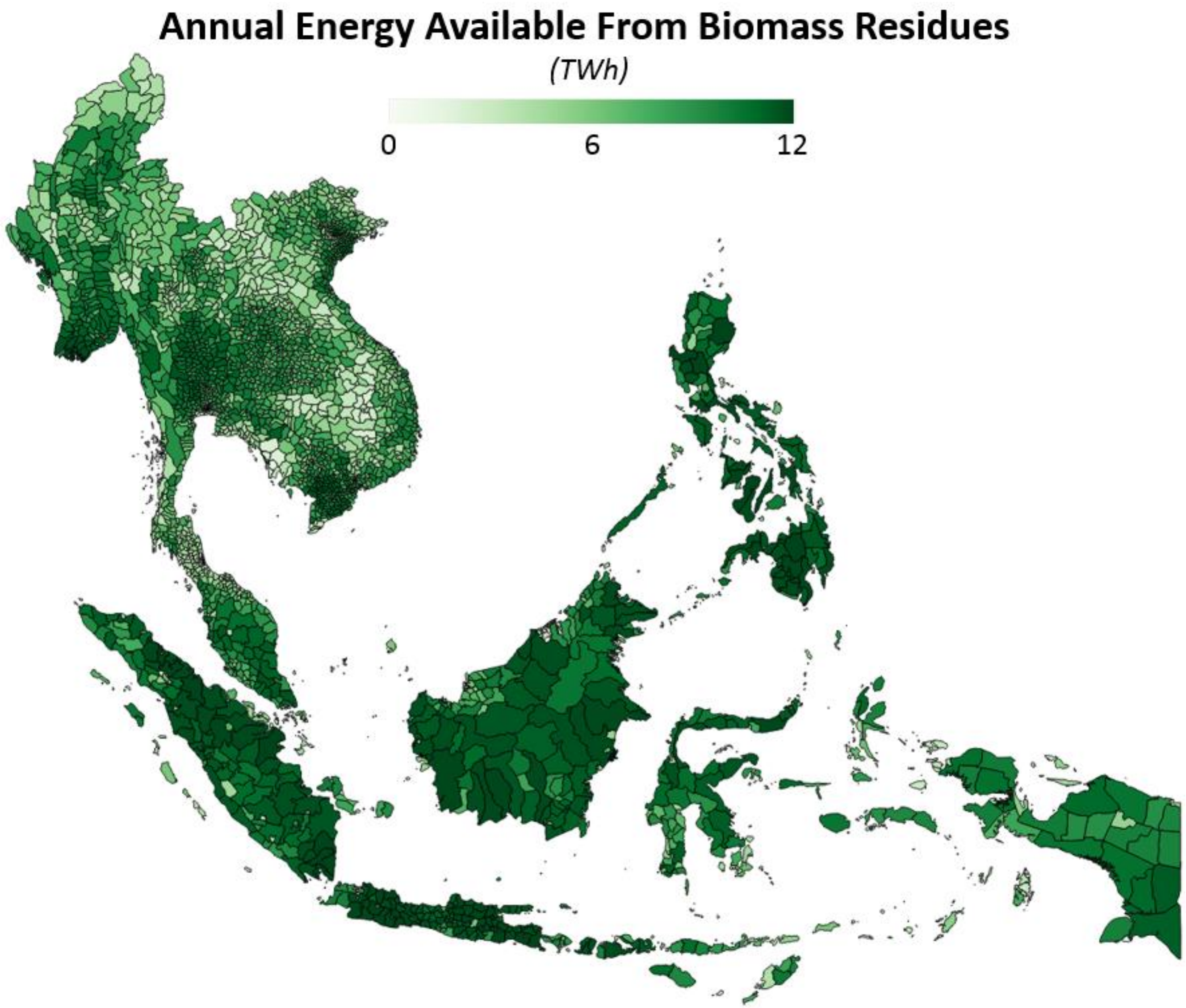

Figure 4.9: Vector of energy available from all biomass residues in ASEAN at high resolution

4.4 Identification of the critical residues

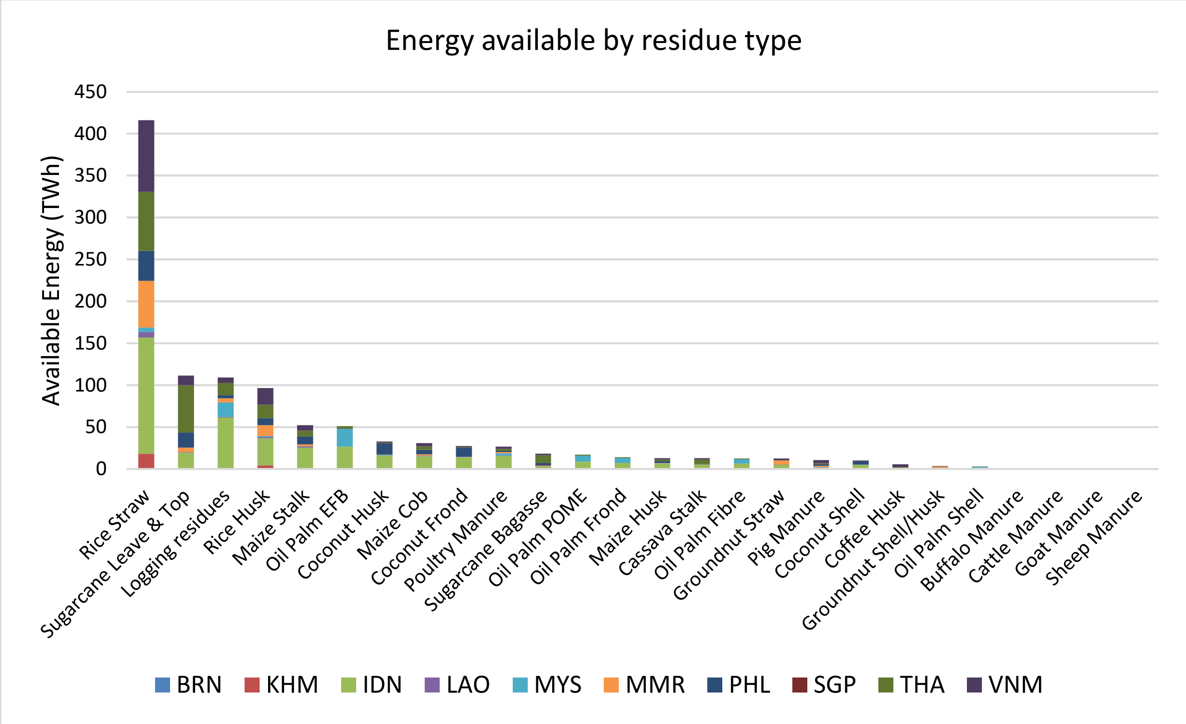

Figure 4.10: Energy available from different residue types in the different ASEAN Countries

This evaluation comprises of 26 different biomass residues that are calculated for 10 different nations. However, the energy available from the residues is distributed unequally across the residue types. Figure 4.10, shows the distribution of energy available from different residue types in different ASEAN countries. It is seen that the major contribution comes from rice straw. In fact, the top six residue types, viz. Rice Straw, Sugarcane Leaves and Top, Logging Residues, Rice Husk, Maize Stalk and Oil Palm EFB, contribute to almost 77% off all the energy from biomass residues in ASEAN. When dealing with the countries individually as well, for majority of the nations (KHM, LAO, MMR, THA and VNM), these 6 residue types contribute to more than 80% of the energy from biomass residues in their country. PHL, MYS and IDN have contributions upward of 63% as well. Only for BRN and SGP, the major contribution does not come from the biomass residue types mentioned.

In the subsequent chapters, transportation, handling, densification, etc. of these residues must be investigated. Considering all the 26 different residues at each step becomes a cumbersome process. The additional effort spent on profiling rest of the 20 residues does not add significant/meaningful results to the Thesis. Hence it is decided that the study would be restricted to the 6 residues mentioned above. The remaining portion of biomass residues will be assumed to behave like the mean value of the residues considered.

4.5 A discussion on carbon neutrality of biomass

In general, biomass can be defined as the plant material derived from the reaction of CO_2 in the air, water and sunlight, via photosynthesis, to produce carbohydrates and lignin that form the building blocks of biomass. Roughly, photosynthesis converts less than 1% of the energy stored in sunlight and stores them as chemical energy in biomass. Using chemical and biological methods, the energy stored in chemical bonds can be recovered. The oxidation of biomass produces CO_2 and H_2O which was absorbed from the atmosphere on a more recent timescale. This process is also cyclic as the CO_2 is then available to produce new biomass again [167]. Biomass energy essentially uses the energy derived from sun through a carbon cycle whose time scales are much smaller than the ones of fossil fuels. Hence it does not contribute to a build-up of CO_2 in the atmosphere, which is the major driver of climate change. This is explained in Figure 4.11.

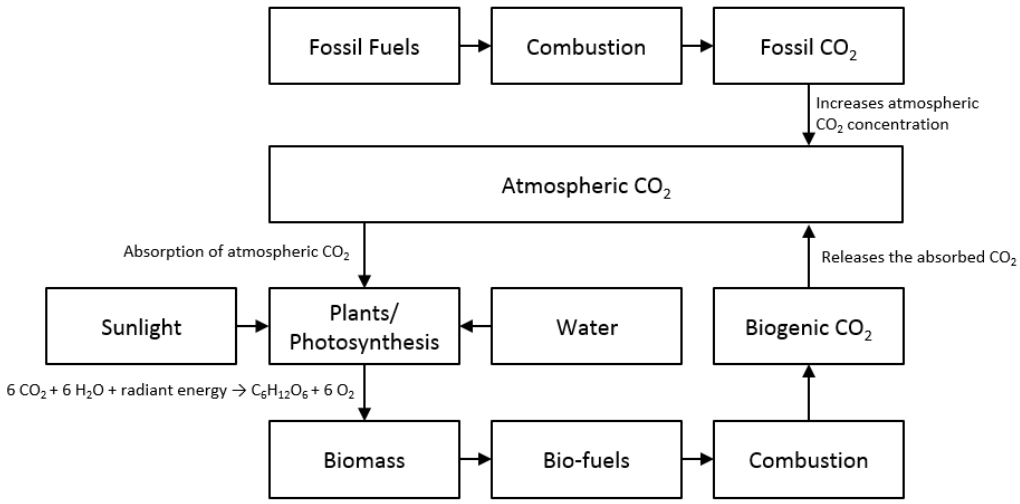

Figure 4.11: The carbon cycle of fossil fuel and biomass

From Figure 4.11, it is observed that the CO_2 released by burning of the carbon in the plants, was essentially what was absorbed by the plants from the atmosphere. Hence biogenic CO_2 is carbon neutral, thus not contributing to GWP. However, in recent times, there have been arguments against this theory [168]–[171]. The discussions are mostly focussed on the use of forest and logging residues for bio-energy. The argument is that, while it takes years for the plants/forests to grow, the burning of wood releases back the CO_2 into this atmosphere all at once, which might take years to be absorbed by the forest again. The other argument is that use of logging residues for bio-energy reduces the carbon stock i.e., the quantity of carbon pool in the forests. If the logging residues are not used for energy purposes, they will be in forest soil stored as carbon which is now released back into the atmosphere. The third argument against carbon neutrality is that there are emissions involved in biomass processing and handling.

In general, an activity in which the CO_2 release and absorption are in balance is defined as a carbon neutral activity. However, in bio-power arena, no common definition is accepted. There are multiple assertions of which the important ones are listed below [172]

- As biomass is naturally carbon neutral, bio-energy is carbon neutral too.
- If growing of biomass absorbs as much CO_2 as released into the atmosphere during its use, then the biomass energy is carbon neutral.
- Only if net life cycle emissions are carbon neutral, the biomass energy is carbon neutral.
- If the biomass energy has a lower net increase in atmospheric GHG as compared to alternative energy activities, then its carbon neutral.

Each of the assertion has issues associated with it. In general, answering the question on the carbon emissions from biomass is not a straightforward task. It depends on several factors [172] like

1. Type of feedstock
2. Time frame of feedstock replenishment
3. Biomass processing and handling techniques
4. Feedstock transportation
5. Energy generation technology

Regarding timeframe of replenishment, for annual crops, as per IPCC guidelines, the carbon stock lost due to harvest (and subsequently use) in that year is the same gained through the regrowth of the plants in the same year [173]. Hence it does not have an impact on the carbon cycle. On the other hand, logging residues, as it deals with forest products, the timeframe plays a role. As discussed by Johnson in his work [168], if the residues are used, it will be eating into the carbon stock. However, Schlamadinger et al. have pointed out in their work, the effect of logging residues removal on carbon stock is limited as eventually, a new equilibrium of carbon storage in forest soil is reached [174]. The removal of logging residues also avoids the emission of methane caused by their decomposition of the residues on the forest floors.

This carbon neutrality issue is simplified in the thesis by adopting the following methodology. It is assumed that the CO_2 released from burning of the biomass is biogenic and hence carbon neutral. The emissions associated with biomass processing and handling are evaluated separately and added to the pathway of energy production. This methodology is consistent with approach 1 stated in work of Muñoz et al. [175]. Also note that even if emissions from biogenic CO_2 sources are evaluated (in a few cases), IPCC does not include them towards the national emission inventory [173], [176], [177]. This methodology is applied only for CO_2. All the other emissions (like methane, PM, etc.) are considered.

The feedstock type dealt with here are agricultural and forest residues. Dealing with agricultural residues is straightforward. Since this work considers only the residues that are left after accounting for its usage in several other processes (refer section 4.3.2), any environmental burden of production of the residues is not associated to the biomass. The LCA (refer section 5.1), defines the starting point to be availability of residues on the field. Same applies to logging residues as well. In general, there is an argument that use of forest residues for energy might cause faster clearing of the forests. However, such studies require a consequential LCA studies which is beyond the scope of this work. Also, since the evaluations are done at macroscopic levels (i.e., country level) and are not project specific (micro level), such complicated approaches are not necessary and would not yield meaningful results.

The emissions of biomass processing and handling will be included in the evaluation. The feedstock is assumed to be transported by diesel trucks. Sea and river transport are not considered in this work. The evaluation of processing and transport emissions are dealt with in section 5.1.2. The efficiency and the emissions of the energy generation technology, the final energy product and their end use plays a major role in determining the emissions of the biomass pathway. They are taken into consideration in this study.

4.6 Identification of ASEAN relevant bio-energy products and recovery pathways

In the previous sections, the biomass residues available in each ASEAN country were quantified and the critical biomass residue types were identified. In this section, the bio-energy products and their pathways of energy recovery, that are relevant to the biomass residues available in ASEAN shall be identified.

4.6.1 Classification of biomass

In general, depending on the chemical content of the biomass, they can be classified into starch/sugar-based, oil-based and lignocellulose-based biomass. Starch/sugar-based biomass are more suitable for bio-ethanol production. Examples of them are sugarcane, corn, etc. Oil based biomass is used for bio-diesel production, examples being soybean, rapeseed, etc. Lignocellulose is more suitable for electricity/heat and bio-ethanol production. Examples of lignocellulosic biomass are agricultural residues (straw, husk, etc.), woody biomass, etc.

Biomass can also be classified into first generation (e.g., energy crops), second generation (e.g., crop residues) and third generation (e.g., algae based) as shown in Figure 4.12. Second and third generation biomass have the benefit that they do not compete with agriculture for land resources. Second generation biomass also has the advantage that the emission associated with production of plants are associated with the crops and not the residues. Since the focus is only on agricultural and forest residues in ASEAN, the study is restricted to second generation, lignocellulosic biomass.

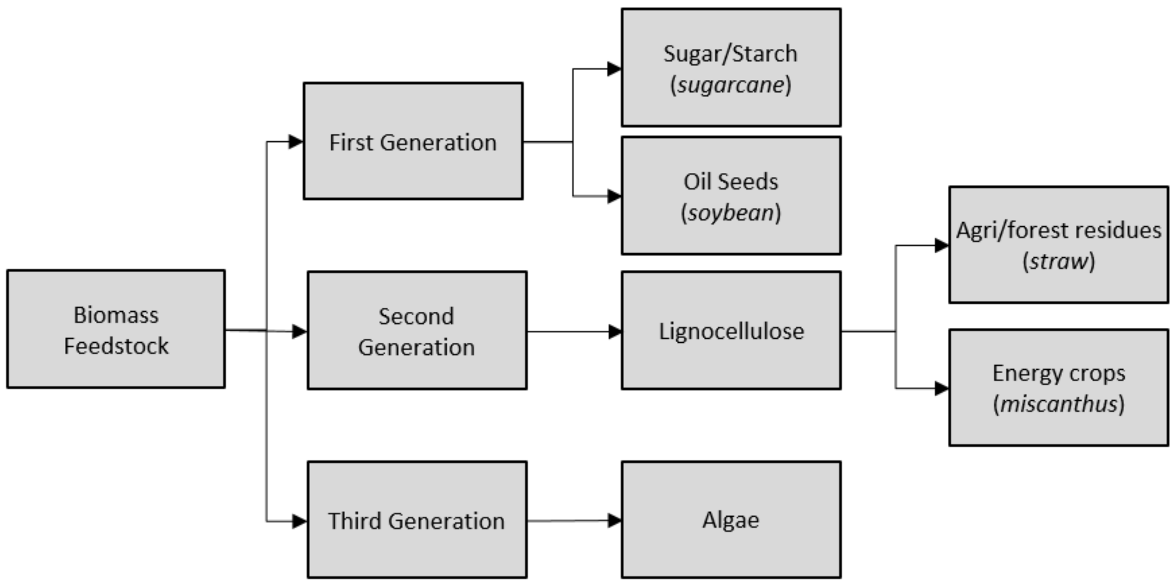

Figure 4.12: Classification of biomass

4.6.2 Kinds of biomass products

Biomass can be converted into four main kind of products, viz. Electricity, Heat, Biofuels and Chemical products [167], [178]. Since this thesis focusses on transport only, the heat and chemical products are left out of the scope of the work. Electricity can be used in transport through BEVs and hence are considered for this study. Biofuels can be classified into solid, liquid and gas as shown in the Figure 4.13 [179]. Liquid biofuels, namely bio-ethanol and bio-diesel are most suited for transport. Bio-diesel production requires oil-based feedstock. However, it was observed earlier in this chapter that the residues available in ASEAN are lignocellulose based. Hence this thesis shall discuss only bio-ethanol. The biomass end products under consideration are bio-electricity and bio-ethanol.

Solid Biofuels	Liquid Biofuels	Gaseous Biofuels
• Wood Pellets • Wood Chips • Briquettes • Firewood	• Biodiesel • Bio-ethanol	• Biogas • Biomethane • Syngas

Figure 4.13: Classification of biofuel

4.6.3 Bio-energy recovery pathways

Pathways of energy recovery from biomass can be classified into thermochemical, biochemical and chemical processes. Each process is studied in detail to identify the ones that are best suited for the kind of biomass feedstock and energy products under consideration.

Thermochemical process: It is the use of heat in combination with airflow, to promote the chemical transformation of biomass into energy or chemical products [180]. Based on the amount of airflow, pressure and temperature range, thermochemical processes can be further classified into combustion, gasification and pyrolysis. Combustion is the direct burning of biomass in excess air to produce heat which can be converted into electricity in a steam turbine. Combustion also produces ash and flue gases. Pyrolysis on the other hand is the chemical decomposition of biomass in the absence of air [181]. It occurs at temperatures of 400-800 ^{o}C. It produces pyrolysis gas and char. Pyrolysis gas can be converted into electricity through gas engines or gas turbines. The conditions of pyrolysis can also be modified to produce other products such as bio-oil. Gasification is the partial oxidation of biomass at lower airflow rates to produce syngas/producer gas. They occur at temperature greater than 800 ^{o}C. The char production is lower in this case. Syngas, like producer gas can be converted into electricity through IC engines or gas turbines [182]. While gasification and combustion have achieved commercial application already, pyrolysis is still in its early stages of development and hence is not analysed in this thesis [183]. Likewise, chemical transformation of syngas/producer gas to produce fuels are also not considered owing to their low level of technological maturity lack of commercial viability and poor efficiency.

Biochemical process: Biochemical processes deals with the breakdown of biomass into gaseous and liquid fuels with the use of bacteria, microorganisms and enzymes [184]. The main outcome of this processes is biogas and bio-ethanol. The most common biochemical processes are anaerobic digestion and fermentation. The anaerobic digestion is more appropriate for feedstock with higher water content, such as animal manure and POME [183]. However, as seen from the previous chapter, they form only a very minor portion of biomass feedstock in ASEAN. Hence, anaerobic digestion is not considered. Fermentation of lignocellulosic biomass yields bio-ethanol. There are three major steps involved in the process. Pre-treatment of biomass is done to increase the accessibility to the enzymes. Following this, hydrolysis of biomass is done to breakdown the polysaccharides into monomer sugars. In the third step, these sugars are fermented into bio-ethanol with the use of different microorganisms [184]. The products of fermentation might have to be treated further to produce fuel grade ethanol.

Chemical process: It is the use of chemical reactions such as transesterification to convert the oil extracted from biomass into bio-diesel. This is more suited for oil-based feedstock. As the feedstock available in ASEAN is not suited for this, it is not considered in this study.

Figure 4.14 gives an overview of all the biomass energy recovery pathways. Of these, direct combustion, gasification and fermentation are the processes that are considered in this study. Hence, the end products to replace the energy demands of transport sector based on available biomass residues and the energy conversion technologies are chosen to be bio-electricity and bio-ethanol.

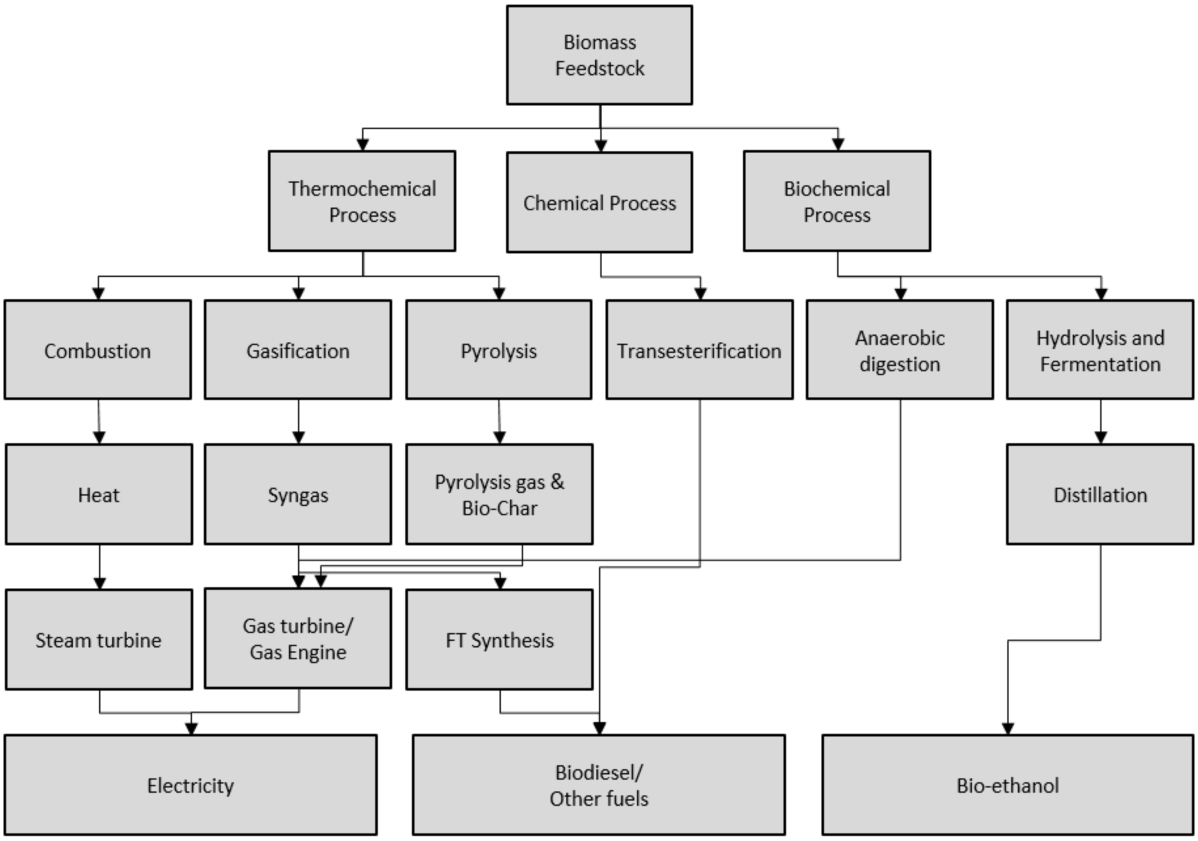

Figure 4.14: Bio-energy pathways for energy recovery from biomass

5 Emission saving potential of bio-energy use in ASEAN's transport

This chapter aims to estimate the emission saving potential of use of bio energy in the road transport sector of ASEAN countries. It has three sections. In the first section, the various pathways of energy product production identified in the previous chapter shall be analysed. The emissions of these pathways would be compared using life cycle assessment techniques. This would constitute the WTT emissions of bio-energy-based transport. Biomass in its raw form is associated with low volumetric energy densities. Hence the impact of the various biomass densification processes on the overall emissions would be studied. Biomass is also associated with large collection areas. Hence the impact centralisation/decentralisation shall have on collection radius and the overall emissions will also be discussed. In the second section, the total bio-energy demand from the transport sector for various scenarios will be estimated. The energy needs will be calculated for different levels of bio-energy penetration in order to match the supply with demand in each country. The TTW emissions of bio-energy based transport sector is evaluated as well. In the final section, these two results shall be combined with the findings of chapter 3 and 4 to estimate the total emission saving potential of use of bio-energy in transport sector in ASEAN.

5.1 Estimation of emissions of energy recovery from biomass - methodology

The biomass resources, energy conversion technologies and the bio-energy products to be used in transport sector have been identified. This section deals with the pathway of energy recovery and the emissions associated with it. The emissions will be evaluated using LCA techniques.

In general, conventional fuels have the advantage of very high power densities (in this sense defined as power produced per unit land area) when compared to renewable energy sources [185]. The land area required for renewable energy sources is a lot higher than the conventional energy source. The typical range of power densities of various energy sources are shown in Table 5.1 [186].

Power Source	Power Density (W/m²)	
	Low	High
Natural Gas	200	2000
Coal	100	1000
Solar (electric)	4	9
Solar (thermal)	4	10
Wind	0.5	1.5
Biomass	0.5	0.6

Table 5.1: Power densities of various sources of energy

The power densities include the areas of energy source production/extraction and power conversion (for e.g., coal mines and the coal power plant). Biomass lies on the lower end of the power density spectrum as photosynthesis is very inefficient energy conversion process. Therefore, large cultivation areas are required for the biomass. The values for biomass in Table 5.1 refers to first generation biomass energy, i.e., energy crops. The focus in the thesis is on second generation biomass which deals with only residues. Hence the power density values will be even lower. Thus, in terms of emissions, transportation of biomass shall play an important role.

In general, larger powerplants can use the biomass at better efficiencies, owing to higher temperature of operation, lower heat losses, better process optimisation, etc [187]. Bigger powerplants also produce lesser emissions per unit energy produced [188] (refer section 5.1.1). However, a bigger powerplant would require a much larger collection area, due to the low power distribution density of biomass. This would have a direct impact on the transportation emissions. Biomass is also characterised by low volumetric energy densities. Biomass densification can help reduce the transport emissions. However, they cause some emissions upfront. Hence a study on the combined impact of size of powerplant, transport distances and biomass densification processes become necessary.

Figure 5.1 denotes the pathways of energy recovery from biomass residues in ASEAN along with the system boundary. As discussed previously, since we are dealing with second generation biomass, the production of biomass is not included in the system boundary. The description of acquisition of life cycle inventory for this LCA is split into 3 parts, viz. biomass powerplant emissions and efficiency (section 5.1.1), biomass transportation emissions (section 5.1.2) and biomass densification emissions (section 5.1.3). Each of the process must be done for every country and for each crop type. The functional unit for the study shall be 'per unit km driven by a mid-size passenger car'.

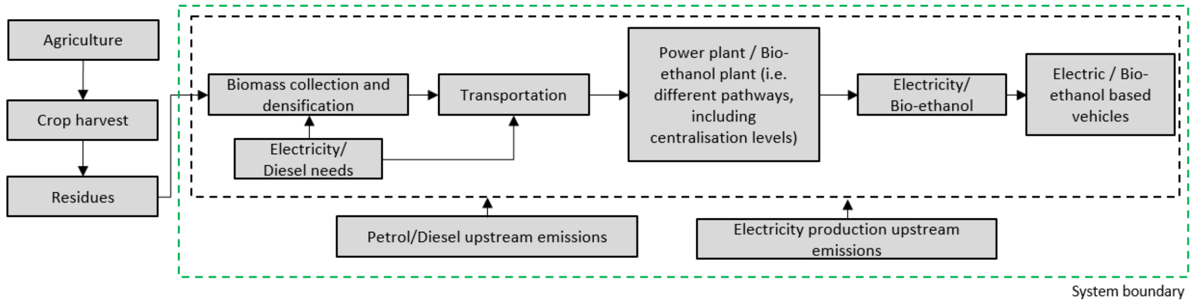

Figure 5.1: Pathways of energy recovery from biomass residues

5.1.1 Efficiency and emissions of biomass powerplants

Though the CO_2 emissions from biomass combustion are biogenic and do not contribute to GWP, there are other emissions occurring at the power conversion plant which needs to be accounted for. Thus, it is necessary to create their emission inventory. Similarly, the biomass input required depends on efficiency and capacity of the powerplant. Hence it becomes important to establish the relationship between powerplants and their efficiencies.

5.1.1.1 Efficiency

To the best of our knowledge, standard curves representing the relationship between the capacity of a powerplant and its efficiency is not found in the literature for all powerplant types under consideration. Hence, an effort is made to establish this relationship. A large database of different biomass power plant and ethanol production plant was created [55], [189], [198]–[207], [190], [208], [191]–[197]. The initial attempt was to do a regression analysis of the datapoints collected. However, a good data fit was not possible with the amount of datapoints available. However, we were able to find a pattern in the efficiency of a powerplant against the capacity. We categorise the powerplant into 3 sizes (2 for bio-ethanol) and found an average efficiency for each powerplant capacity. The capacities and their respective efficiencies are found in the plot in Figure 5.2. Though the general notation for capacity of ethanol production plant is Ml/a, it has been converted into MW (using the annual full load hour and the energy content of ethanol) for the sake of uniformity.

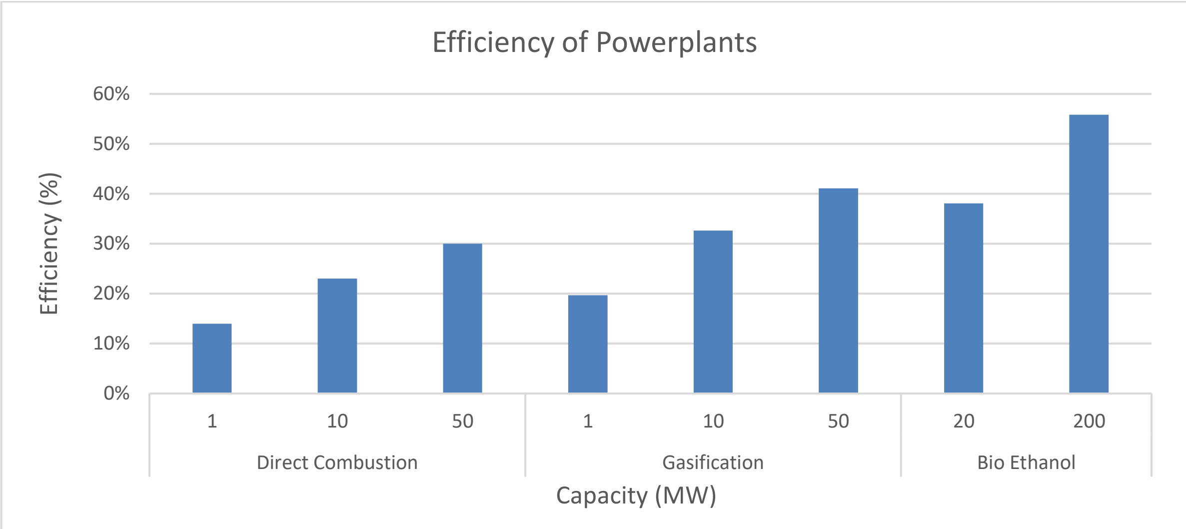

Figure 5.2: Efficiency of powerplants for different capacities for different technologies

A clear trend of increase in efficiency is observed with the increase in capacity for all the different technologies. There is almost a doubling of efficiency from 1 MW to 50 MW when considering power generation technologies. Bio-ethanol production process is more efficient than the electricity production process as the former is a chemical transformation process whereas the latter is a thermal conversion process. At this level, these two are not comparable and need to be compared on the common functional unit (which is done later).

5.1.1.2 Emissions

Evaluation of the emissions of power conversion technologies, especially for second generation biofuels was a complex task. Standard life cycle inventories did not include emission inventories of all the powerplant under consideration, especially for the different capacities. An approach similar to the estimation of efficiency of these powerplants was also attempted. However, the databases that provided information on the efficiency did not provide the data on the emissions. Nevertheless, there are a few studies [55], [190], [191], [209], [210] that gives the air emissions of major pollutants like methane, N_2O, NO_X, etc. for different sizes of direct combustion steam turbine powerplant. These emissions are normalised into their impact category using the impact assessment method mentioned in chapter 3. The GHG emissions refers only to those of CH_4 and N_2O. For gasification, not as many datapoints were available. However, with the minimal data available, the emissions are evaluated. If emissions are not available for a particular size, then it is evaluated by normalising it based on the feedstock input. For bio-ethanol, none of the datapoint that provided information on efficiency gives the data on emissions. Hence the value was taken from the JRC study. JRC gives the value for a 150 MW powerplant that produces bio-ethanol from wheat straw. The emissions of the smaller powerplants are evaluated by normalising the value for feedstock input. This thesis mainly focuses on the GHG emissions and we have decided to assume the biogenic CO_2 emissions to be carbon neutral. Therefore, this simplified approach remains valid. The accumulated data is shown in Table 5.2.

		Direct Combustion			Gasification			Bio-Ethanol	
Capacity	*(MW)*	**1**	**10**	**50**	**1**	**10**	**50**	**20**	**200**
GHG	*(g CO_2 eq/kWh)*	12.66	25.18	24.41	10.39	6.28	0.06	19.51	13.32
AP	*(g SO_2 eq/kWh)*	0.56	0.52	0.84	0.58	0.43	0.28	0.00	0.00
PM 2.5	*(g PM 2.5/kWh)*	0.88	0.10	0.02	0.40	0.04	0.02	0.00	0.00

Table 5.2: Emission inventory of the powerplants for different capacities

5.1.2 Emissions of biomass transport

Evaluation of the emissions of transport is split into 2 sections. One is the specific truck emissions which depend on the kind of truck, loading levels, etc. The other is the transport distance which depends on the type of powerplant, its capacity, crop type, etc.

5.1.2.1 Specific truck emissions

It is assumed that the biomass residues are transported by road by diesel powered, articulated trucks. The specific emission of the truck depends on the loading level. The loading levels depend on the biomass type and the level of densification, which is discussed in section 5.1.3. There are multiple sources such as GREET, ecoinvent, COPERT, etc. which give the value of specific emission of diesel truck. However, COPERT was chosen for the purpose as it provides the specific emissions of truck for different loading levels. For this thesis, three loading levels, viz. <25%, 25-75% and > 75% are chosen. The vehicle of choice is heavy duty, articulated truck 40-50 t of euro III standard. The maximum loading capacity of the truck is taken to be 37 t and the maximum transport volume is taken to be 87.5 m^3. An average speed of 35 km/hr is assumed. Table 5.3 provides the values of the specific emissions and the energy consumption of the truck. The LCIA method used it the same as the one mentioned in chapter 3. The upstream emission of diesel production has already been described in 3.

Loading level	**GHG**	**AP**	**PM 2.5**	**Diesel needs**
	(g CO_2 eq/km)	*(g SO_2 eq/km)*	*(g PM 2.5/km)*	*(MJ/km)*
0 - 25%	839.9	3.85	0.26	11.25
25 - 75%	1209.0	5.22	0.30	16.23
75 - 100%	1557.6	6.55	0.35	20.92

Table 5.3: Specific emissions and energy consumption of diesel transport truck

The loading levels are determined by level of densification. The threshold biomass density is 423 kg/m^3. If the biomass is denser than this value, the truck is assumed to be fully loaded. If the density is lesser than the threshold value, then the loading level is determined by the maximum loadable biomass (restricted by volume) and the maximum carrying capacity of the truck.

5.1.2.2 Biomass transportation distances

As seen from the section 5.1.1.1, larger biomass powerplant has higher energy conversion efficiency. However, they also require more biomass input. Hence, larger powerplants require bigger collection area, which increases the transportation distance. In this section, a relationship between the powerplant capacity and transportation distance is established for each residue type and power generation technology.

Chapter 4 provides the data on biomass distribution at sub district level. The approach for evaluation biomass transportation distances is as follows. An arbitrary point (centroid of a region) is chosen for the location of the powerplant for each biomass type. Based on the capacity, efficiency and operating hours of a powerplant, the annual biomass requirement is estimated. If the required biomass is available within that region, i.e., locally, then the approach shown in section 5.1.2.2.1 is followed. If the biomass locally available in region of powerplant is not sufficient, then the biomass from neighbouring region is imported. This is explained in section 5.1.2.2.2.

5.1.2.2.1 Local biomass

The biomass need for each powerplant is evaluated using,

$$B = \frac{S \cdot FLH}{\eta} \ (MWh) \qquad \text{(eq. 5.1)}$$

, where B is the annual biomass needs of the powerplant, S is the capacity of the powerplant, FLH is the annual full load operating hours and η is the efficiency of the powerplant. The approach for the evaluating the biomass transportation work (BTW) is adopted from [211]. BTW defines the amount of biomass transported over a certain distance. The general unit of BTW is '*tonne km*'. In this the work however, the unit of BTW used is '*MWh km*'. The mass is converted into energy content using LHV. Having the unit of energy (MWh) instead of mass (tonne) in the denominator simplifies the association to the final output of the powerplants, which is also a unit of energy. The plant is assumed to be located at the centroid of the region. Each region is assumed to be a circle. Assuming the radius of the circle to be '*R*',

$$BTW = \int_0^R \rho \cdot (2 \cdot \pi \cdot r) \cdot r \cdot \tau \cdot dr \ \ (MWh\,km) \qquad \text{(eq. 5.2)}$$

$$BTW = \frac{2}{3} \cdot \pi \cdot \rho \cdot R^3 \cdot \tau \ \ (MWh\,km) \qquad \text{(eq. 5.3)}$$

,where 'ρ' is the biomass distribution density ('*MWh km^{-2}*') and 'τ' is road tortuosity factor. ρ is evaluated by dividing the regional biomass availability by the area of the region. τ defines the ratio of actual distance travelled to the displacement. A value of 1.5 is taken for τ literature. The relationship between biomass requirement and land area could be established as,

$$B = \rho \cdot \pi \cdot R^2 \ (MWh) \qquad \text{(eq. 5.4)}$$

Hence BTW is,

$$BTW = \frac{2}{3} \cdot \pi \cdot \rho \cdot \tau \cdot \left(\frac{S \cdot FLH}{\pi \cdot \eta \cdot \rho}\right)^{\frac{3}{2}} \ (MWh\,km) \qquad \text{(eq. 5.5)}$$

5.1.2.2.2 Imported biomass

When biomass inside the region of a powerplant is not enough to provide its annual needs (as per eq. 5.1), then it shall be imported from the neighbouring regions. The methodology for evaluating the biomass transport work of imported biomass is as follows. Using GIS software, regional vector and road network the distance between the centroids of the region containing the powerplant and all the other regions is estimated. Then the distances are arranged in ascending order to identify the closest regions. The biomass availability of each region is multiplied by the transport distance and summed up, till the total amount of biomass available satisfies the requirement of the powerplant. The said process is pictorially represented in Figure 5.3. The same is repeated for each country and for each residue type.

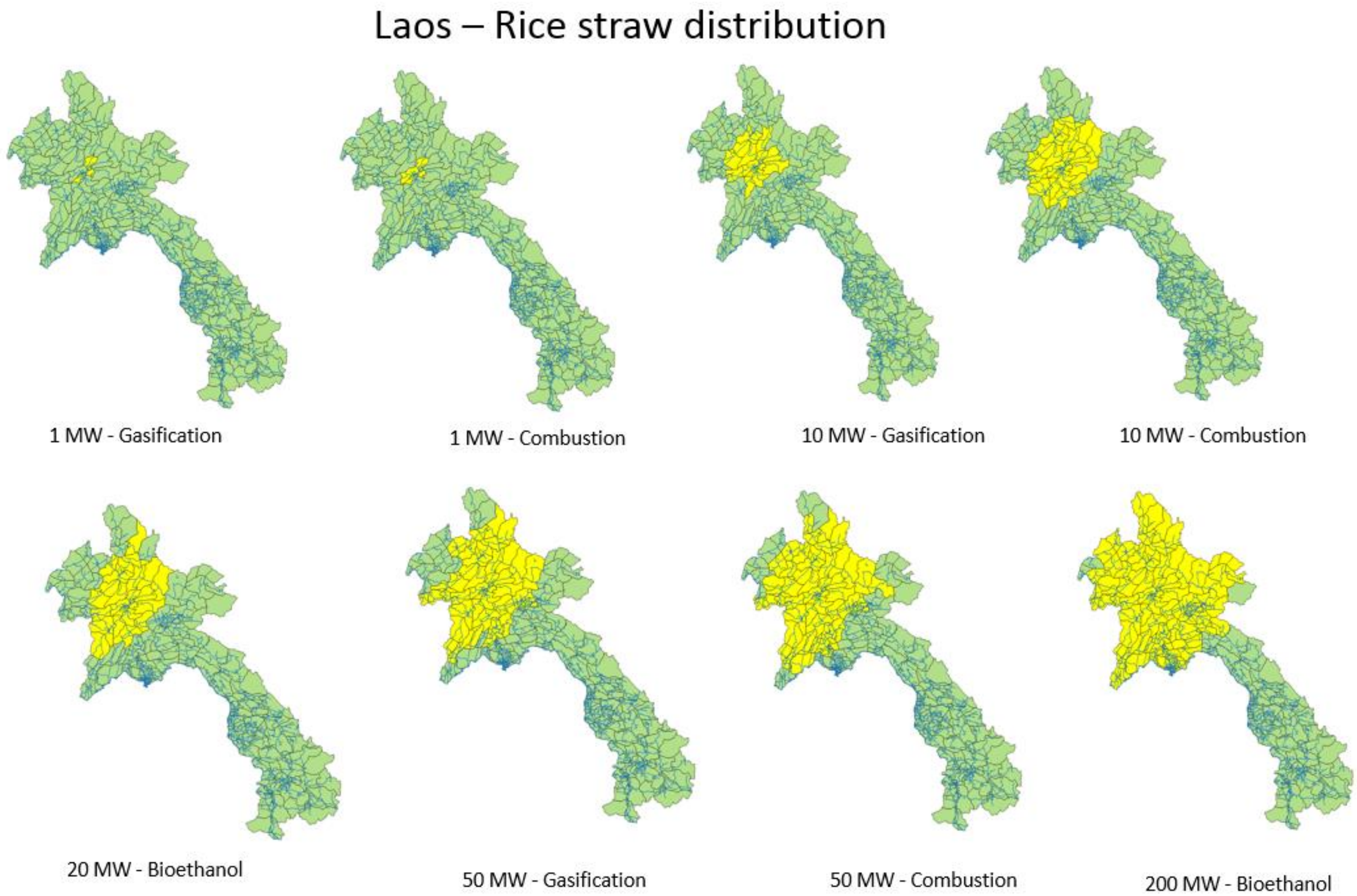

Figure 5.3: Area required for different biomass powerplants of different capacities

5.1.2.2.3 Estimated values of BTW and key observations

The method for evaluation of BTW is semi-automated. Not all the capacities of the powerplant mentioned previously in section 5.1.1 are feasible for all the residues. The main restriction on the maximum size comes from the total availability. In addition to that, most countries in ASEAN are broken down into smaller islands. Since we do not consider ship transport in this thesis, a powerplant is restricted by the total biomass available in its island only. These restrictions have been considered in the study. For instance, the total amount of sugarcane trash available in Malaysia technically can allow for a 10 MW combustion powerplant. However, as the total biomass is split between two big islands, the maximum allowable biomass plant for this type of biomass is 1 MW combustion only. The maximum size and type of powerplant for each country is mentioned below in Table 5.4. The colours represent each type of powerplant. Blue represents combustion, yellow represents gasification and green represents bio-ethanol powerplants.

	Maximum installable capacity									
	BRN	**KHM**	**IDN**	**LAO**	**MYS**	**MMR**	**PHL**	**SGP**	**THA**	**VNM**
	(MW)									
Rice Husk	0	50	200	50	50	200	200	0	200	200
Rice Straw	0	200	200	200	200	200	200	0	200	200
Sugarcane Leaves & Top	0	10	200	10	1	200	200	0	200	200
Maize Stalk	1	50	200	50	1	50	200	0	200	200
Oil Palm EFB	0	0	200	0	200	0	1	0	200	0
Logging residues	1	1	200	10	200	200	1	0	200	200
Others	1	200	200	200	200	200	200	1	200	200

Table 5.4: Maximum installable capacity for each crop type in each country.

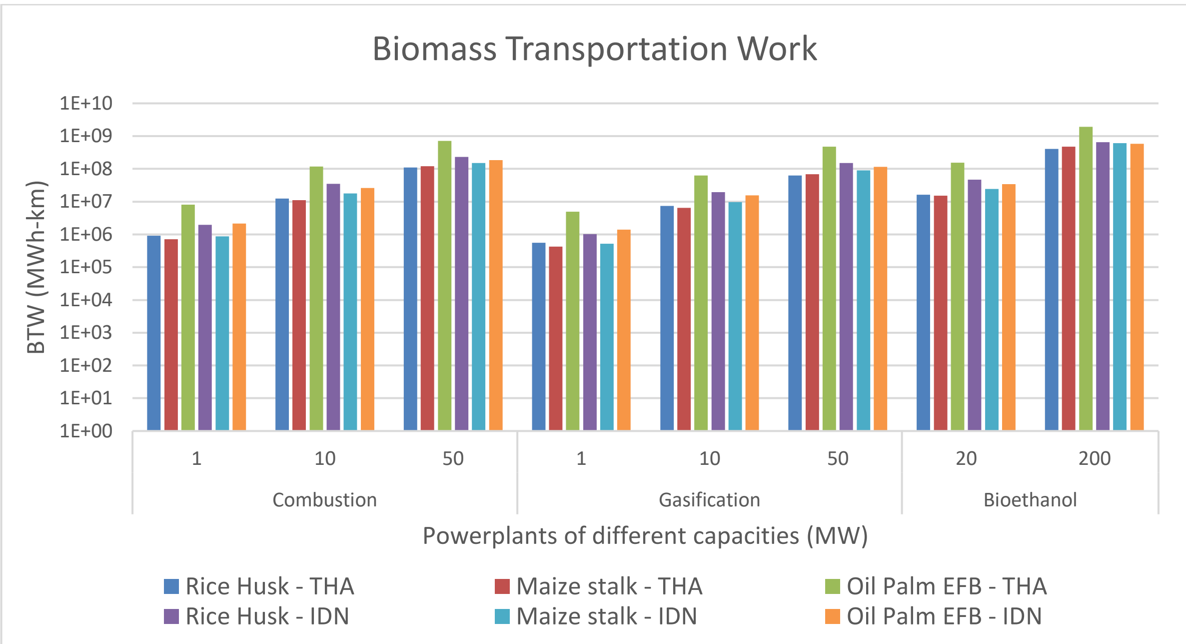

Figure 5.4: BTW for selected crops for selected countries

For each country, for each biomass types, 3-5 arbitrary powerplant locations are chosen to account for the randomness. The BTW is then the average of these values is evaluated. Selected results of BTW are shown in Figure 5.4. However, some of the major observations from the study are presented below.

- The relationship between BTW and installed capacity is non-linear.
- The BTW for the different crop within the country varies largely.
- The BTW for same residue, between different countries also varies substantially and a general trend is not visible.
- The dependence of BTW on location of powerplant is higher for lower capacities (of powerplant) and lower for higher capacities.
- A universal pattern is not visible and hence, the evaluation of BTW must be case specific.

The above inferences further strengthen the reasoning for identifying residue location with greater accuracy.

5.1.3 Emissions and energy needs of biomass densification

Unprocessed biomass residues are characterised by low bulk densities. For example, unprocessed straw has an average volumetric density of about 100 kg/m^3. This combined with low specific energy (around 1.7 – 4.6 kWh/kg) reduces the amount of energy that could be transported per trip. This is very low as compared to other solid fuels like coal that has a bulk density of 800 – 1000 kg/m^3 with a specific energy of 6.7 – 9.7 kWh/kg. Hence there is a need to densify the biomass. As seen from section 5.1.2.2, the threshold density of biomass transport using the truck considered in this thesis is 423 kg/m^3. Hence if biomass is transported at unprocessed state, it would mean that the truck can be loaded only to a fourth of its capacity. This increases the biomass transport emissions by 4 folds. By densifying the biomass using the standard densification processes, the amount of load that can be carried by a truck per trip can be increased, thus reducing the transport emissions. However, the biomass densification process requires some energy. Hence, there is a need to assess the energy needs and emissions of biomass densification processes in tandem with truck transportation to identify the least emissive combination. Biomass can be densified into bales, briquettes, pellets, pucks, cubes, etc. The most common biomass densification processes are baling, briquetting and pelleting. Figure 5.5 shows the images of biomass at different levels of densification.

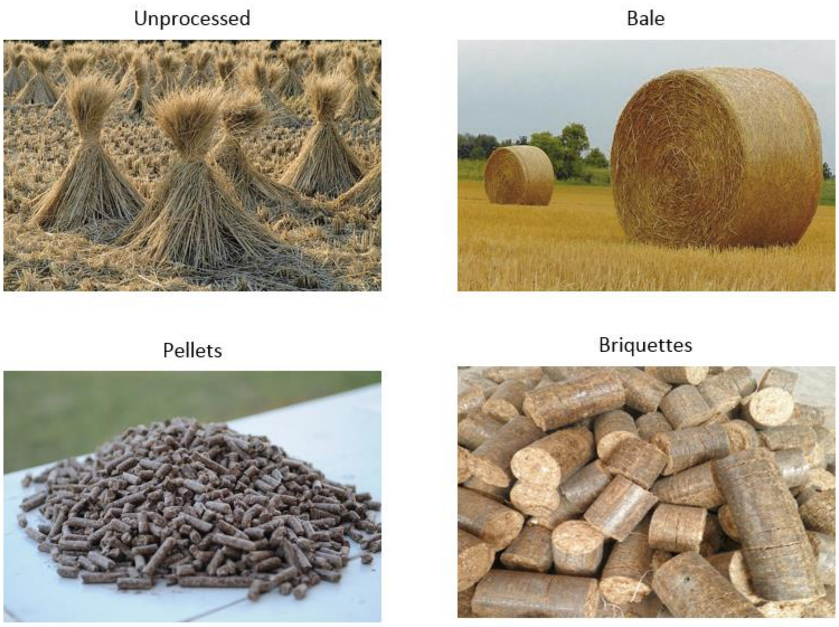

Figure 5.5: Images of biomass residues at different levels of densification

Baling is usually done by machines that are either attached to tractors or standalone machines. They bundle the straw and other waste into bales by densely packing them together. They generally double the volumetric energy density of the loose biomass, to about 190 kg/m^3 [212]. Since baling process uses diesel, it produces local emissions. The diesel production causes some upstream emissions as well. The local emissions associated with baling process are taken from ecoinvent and the upstream emissions of diesel production is taken from Chapter 3. The name of the process is 'Baling {RoW}|processing |Cut-Off, U'. The LCIA method used is the same as in the previous cases. Table 5.5 shows emission of the entire chain of baling (including upstream diesel production emissions).

Diesel Needs *(MJ/t)*	**GHG** *(kg CO_2 eq/t)*	**AP** *(kg SO_2 eq/t)*	**PM** *(kg PM 2.5/t)*
45.75	9.9325	0.0542	0.008372

Table 5.5: Energy needs and emissions of baling

Briquettes produced by briquetting machines have densities higher than baling. This helps reduce the transport emissions by letting the trucks operate at full loads. Typical densities of briquettes range from 500 to 1100 kg/m^3 [52], [213]–[216]. However, it is an energy intensive process that consumes electricity. The different processes involved in different stages of biomass briquette production are, drying, milling, briquetting and cooling of briquettes [217]. The energy consumption involved in each stage is given in Table 5.6 [52]. The emissions arising from briquetting will be calculated using the electricity needs of briquetting and the GEF values calculated in section 5.1.3.1.

Drying *(kWh/t)*	**Milling** *(kWh/t)*	**Briquetting** *(kWh/t)*	**Drying** *(kWh/t)*	**Total** *(kWh/t)*
2.2	7.1	33.3	0.2	42.8

Table 5.6: Energy needs of biomass briquetting

Pelleting is a process similar to briquetting. Pellets are smaller than briquettes and are typically of 6-12 mm in diameter with varying lengths. Like briquetting, pelleting is also an energy intensive process. The sub processes of pelleting are drying, milling, pelleting and cooling. It is estimated that the entire pelleting process consumes 91.3 kWh/t if done on small scale and 74.6 kWh/t if done on large scale [52]. The densities of pellets found in literature vary largely, but lie in the same range as that of briquettes [52][217]. Briquetting achieves the same densification effect with lesser energy needs. Hence, pelleting does not seem to be an energy economic process and it is left out of the scope of this work. For the sake of simplicity, it is assumed that all the process-based biomass is briquetted. The field-based biomass could be briquetted or baled. Further analysis on the combined effect of transport distance, truck emissions and biomass processing emissions need to be carried out to make an informed decision.

5.1.3.1 Grid emission factor

The emissions caused by the production of electricity also known as grid emission factor (GEF) serves as one of the important inputs for the LCA model. It is necessary for evaluating the emissions associated with densification processes such as briquetting or pelleting. In addition to that, the GEF is required for the comparison of proposed pathways with a BEV that derives its electricity from the grid. Hence, it becomes essential to evaluate GEF for the individual countries with good accuracy.

There are a few existing data sources that provide GEF values for the different ASEAN countries. For example, countries like Singapore and Malaysia provide their national GEFs through their national statistics databases [218], [219]. This data however is not provided by all the ten ASEAN countries. The institute for Global Environmental Strategies (IGES) provides a dataset on GEF (only CO_2) of various nations [220], which is mainly intended to determine the baseline emissions of the Clean Development Mechanism (CDM) projects. This consists of data for most of the ASEAN countries. They also differentiate between the operating margin and the build margin. In general, GEFs are calculated based on the powerplant mix. However, ecometrica presented a paper that evaluates the GEF factors of nations with a methodology different from others [221]. They divided the total emission from electricity production of different countries (provided by emission inventory databases like IEA) by the total electricity produced in the country. They presented the GEF for GHGs.

Most of the methodologies in the above-mentioned sources focus on CO_2 or GHG emissions only. For the framework of this thesis, the emission of acidic gases and particulate matter are required as well. In addition to that, for the sake of uniformity and maintaining the same reference year (2014) an indigenous methodology needs to be developed. The method followed for evaluation of GEF in this thesis is as follows

1. Identify the energy mix of electricity production of each nation.
2. Establish the emissions inventory (otherwise known as the life cycle inventory) of the power generation technologies being used.
3. Convert the emissions into meaningful impact categories (i.e., GWP, AP, etc.).
4. Using the grid efficiency, evaluate the GEF.

5.1.3.1.1 Energy mix of electricity generation

In the thesis, operating margin, i.e., the grid emission factor of existing powerplant mix is evaluated. The data on energy mix of electricity production is taken from IEA [112]. Data for Laos alone is taken from the shift project data portal [40] as IEA does not provide the data. Table 5.7 provides the energy mix of electricity generation for the different ASEAN nations expressed as percentage.

	Coal	Oil	NG	Biomass	Waste	Hydro	Geothermal	Solar PV	Wind
BRN	0.0	1.0	99.0	0.0	0.0	0.0	0.0	0.0	0.0
KHM	28.2	10.7	0.0	0.6	0.0	60.5	0.0	0.1	0.0
IDN	52.5	11.5	24.6	0.4	0.0	6.7	4.4	0.0	0.0
LAO	6.2	3.1	0.0	0.0	0.0	90.7	0.0	0.0	0.0
MYS	37.9	2.4	50.1	0.5	0.0	9.1	0.0	0.2	0.0
MMR	2.0	0.5	35.2	0.0	0.0	62.4	0.0	0.0	0.0
PHL	42.8	7.4	24.2	0.2	0.1	11.8	13.3	0.0	0.2
SGP	1.1	0.7	95.3	0.3	2.6	0.0	0.0	0.1	0.0
THA	21.8	1.0	68.7	4.1	0.2	3.2	0.0	0.8	0.2
VNM	23.2	0.4	33.4	0.0	0.0	42.9	0.0	0.0	0.1

Table 5.7: Energy mix of electricity generation (%)

In the above table, the% of electricity generated from coal encompasses all kinds of coal such as anthracite, lignite, etc. The efficiency and emission of electricity production from different types of coal varies considerably. For instance, lignite based powerplant produces 22% more GHG emissions than the hard coal-based ones. Similarly, the data on oil powerplant (on whether its diesel or heavy fuel oil (HFO)) is not given at finer resolution. This issue is solved by auditing the coal and oil production balances provided by IEA [112]. Table A.11 in the appendix provides to data on total quantity of coal and oil (along with the split in type) used for electricity generation purposes in each ASEAN nation. Following ecoinvent's approach for GEF evaluation, it is assumed that anthracite and bituminous coal is burnt in hard coal power plant and sub-bituminous coal and lignite is burnt in lignite power plant. Based on the resource utilisation of the powerplant, the power generation percentage was allocated.

With respect to NG, the efficiency and emissions of conventional gas turbine (GT) and combined cycle gas turbine (CCGT) varies substantially. The electricity production from NG is allocated to conventional GT and CCGT based on the installed capacities of each type of power plant in each country. The share of CCGT and conventional GT for each country is derived from[11], [222] and plotted in Figure 5.6.

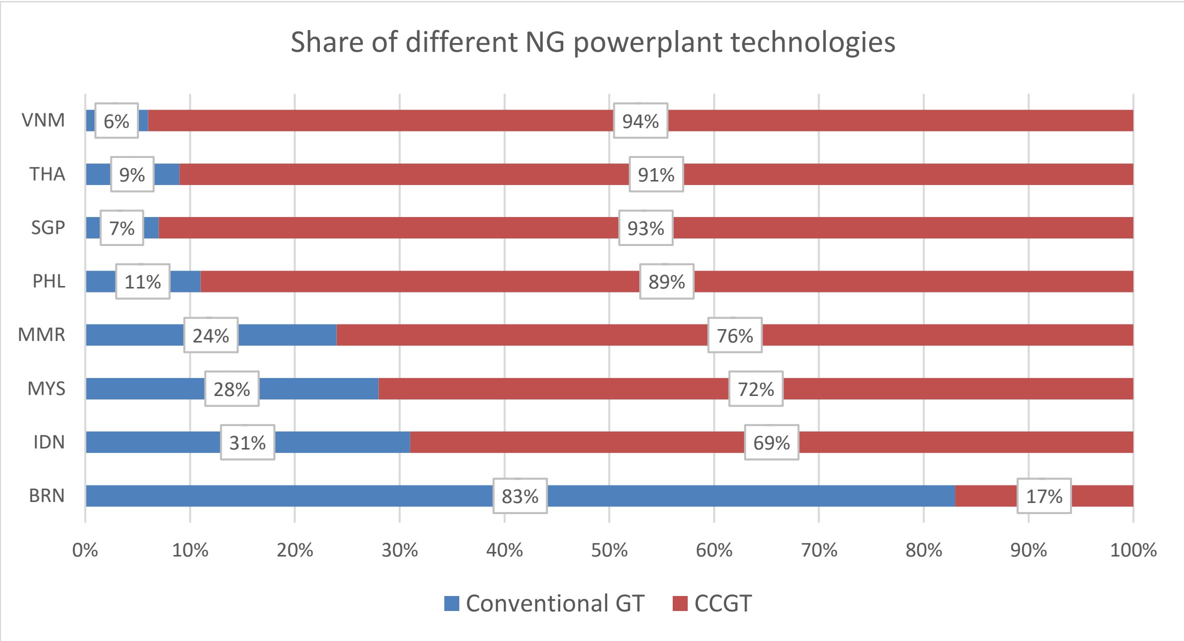

Figure 5.6: The proportion of conventional and combined cycle GT powerplants in different ASEAN countries

5.1.3.1.2 Emission inventory of powerplants

The emission inventory of powerplants is taken from 'ecoinvent'. The 'Cut-Off' system model is preferred over 'APOS' and 'Consequential' system models, owing to its simplicity and robustness. Since there are no specific datasets available for ASEAN, the ecoinvent dataset for rest of world (RoW), is chosen. The emission inventory is chosen for the high voltage (HV) setup. The emission at low voltage (LV) is evaluated by considering the grid losses. The impact assessment method chosen for normalising the emissions is the same as the one chosen in chapter 3. The list of the powerplants considered, their ecoinvent activity name and the emission inventory can be found in appendix (Table A.12).

5.1.3.1.3 Efficiency of the grid and GEF

For evaluating the emission at low voltage (LV), the knowledge of transmission and distribution (T & D) losses of each country is needed. That is, per unit electricity consumed at LV, how many units of energy needs to be produced at HV. The ASEAN Centre for Energy provides this value for each nation [223]. The losses vary from as low as 1.6% in Thailand to 19% in Myanmar. The GEF is thus evaluated using eq 5.6 and eq. 5.7,

$$GEF_{HV} = \sum_{p=1}^{n} em_p \cdot ef_p \quad \text{(eq. 5.6)}$$

$$GEF_{LV} = \frac{GEF_{HV}}{1 - T\ \&\ D_{losses}} \quad \text{(eq. 5.7)}$$

where $p, em_p, ef_p, GEF_{HV}, GEF_{LV}, T\ \&\ D_{losses}$ denote the power plant type, energy mix fraction of the powerplant, efficiency factor of the power plant, GEF at high voltage, GEF at low voltage and transmission and distribution losses respectively. The T & D losses and the GEF of the different countries are tabulated in Table 5.8.

Country	Losses (%)	GHGs (g CO_2 eq/kWh)	Acidic gases (g SO_2 eq/kWh)	PM 2.5 (g PM 2.5/kWh)
BRN	14.0%	666.1	0.376	0.025
KHM	4.3%	523.0	3.119	2.620
IDN	9.8%	988.6	5.245	5.158
LAO	7.1%	172.1	0.892	0.036
MYS	1.6%	676.1	3.757	0.162
MMR	19.0%	290.7	0.352	0.022
PHL	3.7%	675.3	4.638	0.415
SGP	3.0%	455.2	0.387	0.033
THA	1.6%	582.1	2.234	0.893
VNM	8.3%	466.4	2.443	0.107

Table 5.8: Grid efficiency and GEF of ASEAN countries

5.1.3.1.4 Validation of the evaluated GEFs

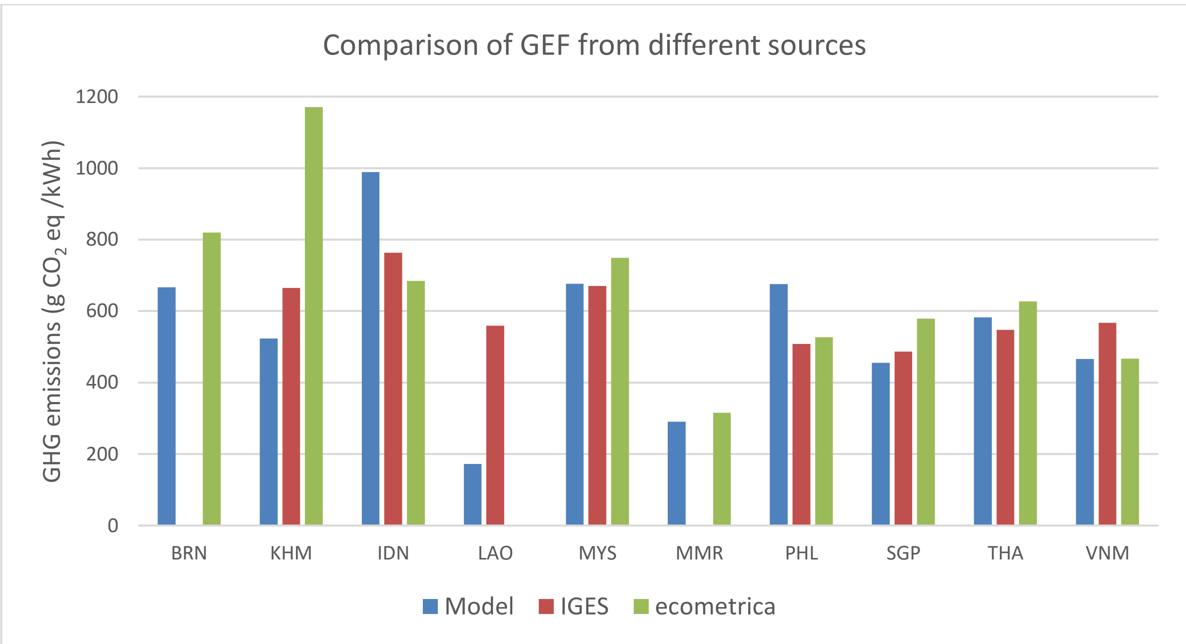

Figure 5.7: Comparison of GEF values acquired from different sources

The above graph shows the comparison of the GHG GEFs derived from different sources. The model developed seems to agree with the one in literature for majority of the countries. However, stark disagreements are observed in a couple of cases. For instance, the GEF of Cambodia predicted by ecometrica is more than twice of what is evaluated by us. The main reason for the same is that the share of fuel type in electricity generation has been fluctuating largely for Cambodia in the past years. The ecometrica evaluation was done for 2011 when the electricity generation was oil products dominated. Whereas in 2014, the main contribution came from hydro power. Similarly, for Laos, the values provided by IGES (which is thrice the value estimated by the model) are evaluated for the year 2010. Reason for the name is not exactly known as not much information is provided on their methodology. However, with 90% of its electricity coming from hydro power, it is unrealistic to have values as high as the ones suggested by IGES. In case of Indonesia, the GEF value estimated by the model developed is higher than both of IGES and ecometrica. However, these values agree with that provided in ecoinvent and other sources [224]. The higher number is also justified by the higher share of fossil fuels (89%), especially coal (53%) in the energy mix of electricity generation.

5.1.4 Defining the functional unit

While the comparison between the within the different electricity production pathways could be made based on kWh of electricity produced, it cannot be compared with bio-ethanol on an energy basis. There needs to be a common function that both the energy products have for making a fair comparison. In this case, 'a km driven by mid-sized passenger car' is chosen. The energy consumption of an electric car is taken to be 1.02 MJ/km. The BEV car does not produce any local emissions. The energy consumption and emissions of a 100% ethanol vehicle is taken from COPERT software. As discussed previously, CO_2 arising from ethanol combustion does not contribute to GWP, however, there are other pollutants such as N_2O, PM, NO_x which needs to be accounted for. The energy consumption of a 100% ethanol vehicle is 3.05 MJ/km. Its emissions are 5.4 g CO_2eq/km, 0.258 g SO_2 eq/km and 0.014 g PM 2.5/km. The reference for comparison is conventional petrol and diesel mid-size car. The emissions of a conventional car differ for each country as well, owing to the average speed of vehicle, climatic conditions and emission standard of the vehicle mix. For instance, in ASEAN, our model suggests that the GHG emission of a petrol car can vary from 211.7 g CO_2 eq/km (VNM) to 325.8 g CO_2 eq/km (PHL). It is decided that the average of all the countries is chosen for comparison. The values are whose emissions are taken to be 280.1 g CO_2 eq/km and 223.3 g CO_2 eq/km respectively for petrol and diesel respectively.

5.1.5 Emissions of energy recovery from biomass residues – Results and key observations

It is not feasible to present and discuss the entire spectrum of the results as there are multiple crop types, energy products and different energy conversion technologies of different sizes involved. Hence only the key findings and trends are discussed and highlighted. Figure 5.8 in next page describes the specific GHG emissions of energy recovery from rice straw in Indonesia.

5.1.5.1 Comparison of the different technologies

The first obvious inference that can be drawn is that both the bio-electricity and the bio-ethanol pathways (in all the configurations considered) perform better than the conventional fuels and hence can offer high emission savings. But it is seen that the bio-electricity pathway produces lesser GHG emissions than the bio-ethanol pathway. Though the efficiency of bio-ethanol conversion is higher than that of bio-electricity (at powerplant level), the BEVs can use the energy produced at efficiencies much higher than the bio-ethanol based IC engine cars. Gasification which has the advantage of higher efficiencies perform better than direct combustion. The higher efficiency of the gasification technology also has an indirect effect on reduction in the upstream transportation and processing emissions (on a per unit energy basis).

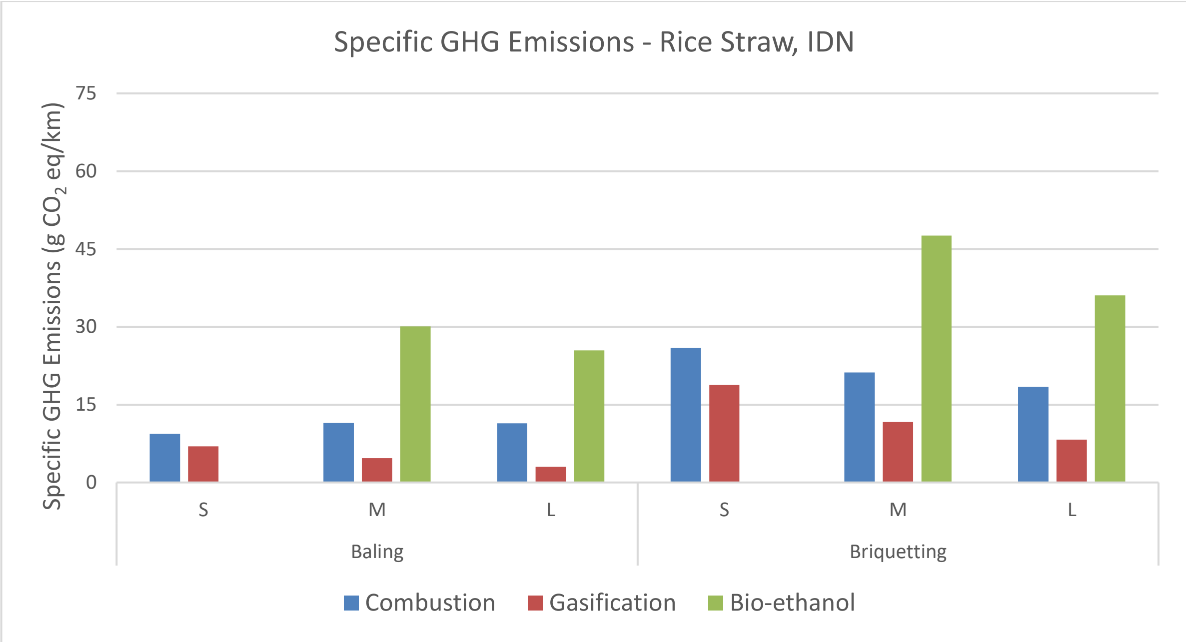

Figure 5.8: Specific GHG emissions of energy recovery from rice straw in Indonesia for different Powerplant technology & sizes and densification techniques

5.1.5.2 Impact of centralisation

The results suggest that the centralisation of energy recovery is advantageous in terms of emissions for both gasification and fermentation technologies. The improved efficiency of the larger powerplants have a greater impact towards emission reduction than the additional emissions caused by the increased transport distances. A minor anomaly was observed though. For rice husk in Laos, a 10 MW gasification powerplant configuration seems to produce lesser emissions than the 50 MW. This is mainly owing to the sparse spatial distribution of the residues and the energy content of the residues under consideration. However, the actual difference in number is insignificant. Hence for all practical purposes, in the calculations made in the following sections, only a 50 MW plant is considered. Considering that they replace more emissive fossil emissions, this assumption is valid as it can offer higher savings in all. Direct combustion on the other hand presents a slightly different story. There is an initial increase in specific emissions from 1 MW to a 10 MW powerplant followed by a decrease when size increases further to a 50 MW powerplant. The variation however is not stark. The main reason for this is the direct emissions from the powerplant emission follows the same pattern as above (refer Table 5.2).

5.1.5.3 Impact of crop types

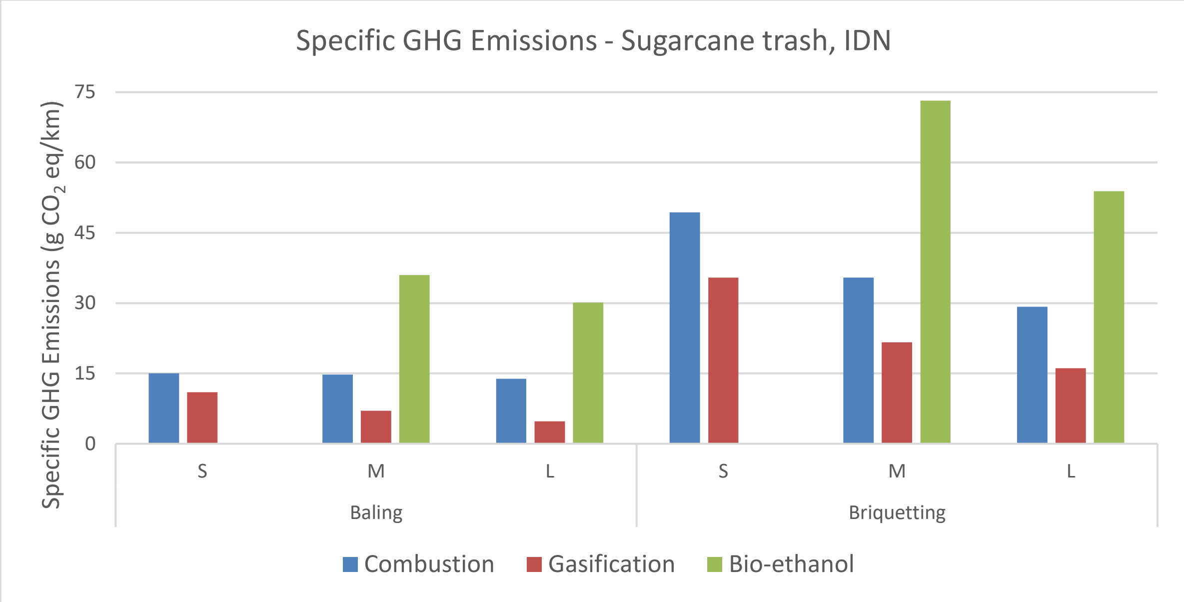

Figure 5.9: Specific GHG emissions of energy recovery from sugarcane trash in Indonesia for different Powerplant technology & sizes and densification techniques

Crop type has an influence on the emissions of energy recovery as well. The primary reason for the same is their differences in spatial distribution and energy content. Figure 5.9 shows the GHG emissions of energy recovery from sugarcane trash in Indonesia. When comparing the results to GHG emission to energy recovery from rice straw in Indonesia (Figure 5.8), we see increased emissions for sugarcane trash. This is due to the lower energy content (per unit mass) of sugarcane trash. Figure 5.10 describes the variation in emissions of energy recovery for various crop residues across all the countries for 1 MW combustion powerplant with baling as its primary energy densification technique.

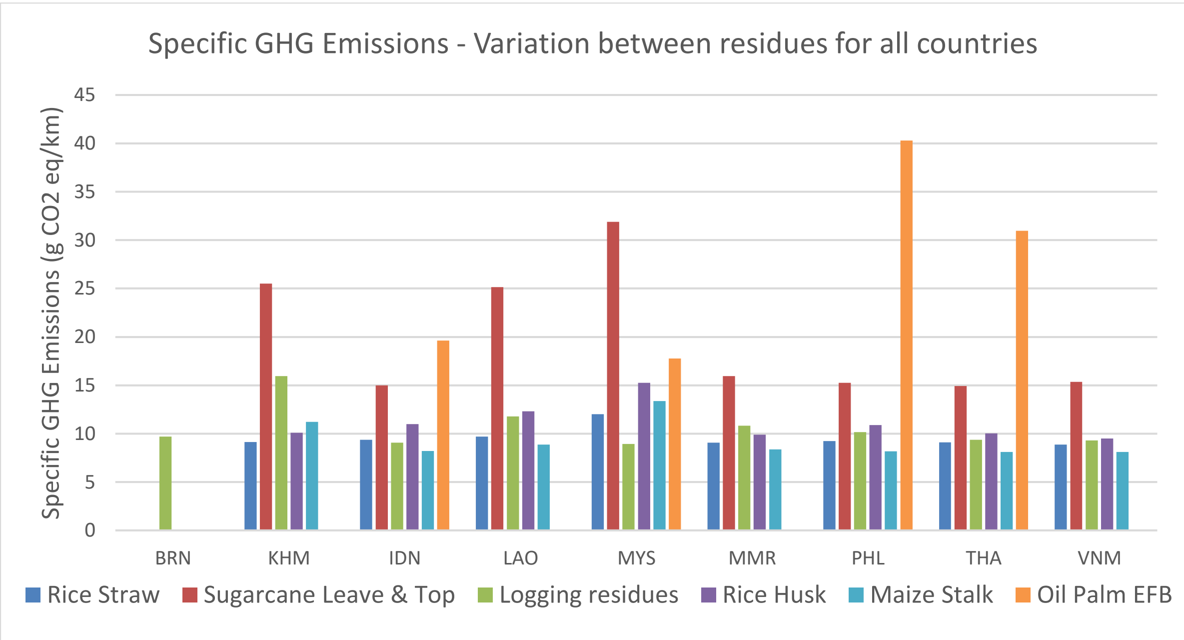

Figure 5.10: Specific GHG emissions of energy recovery from various residues for all the countries, for 1MW combustion powerplant with baling configuration

The difference between the different crop residues is very noticeable. The difference gets even bigger when considering briquetting as GEF varies considerably between the countries. A graph comparing the emissions of energy recovery for various crops across all the countries for 1 MW combustion powerplant with briquetting as its primary energy densification technique is provided in the appendix (Figure A.7). The higher emissions for sugarcane trash and Oil Palm EFB is indicative of their low specific energy.

5.1.5.4 Variation between countries

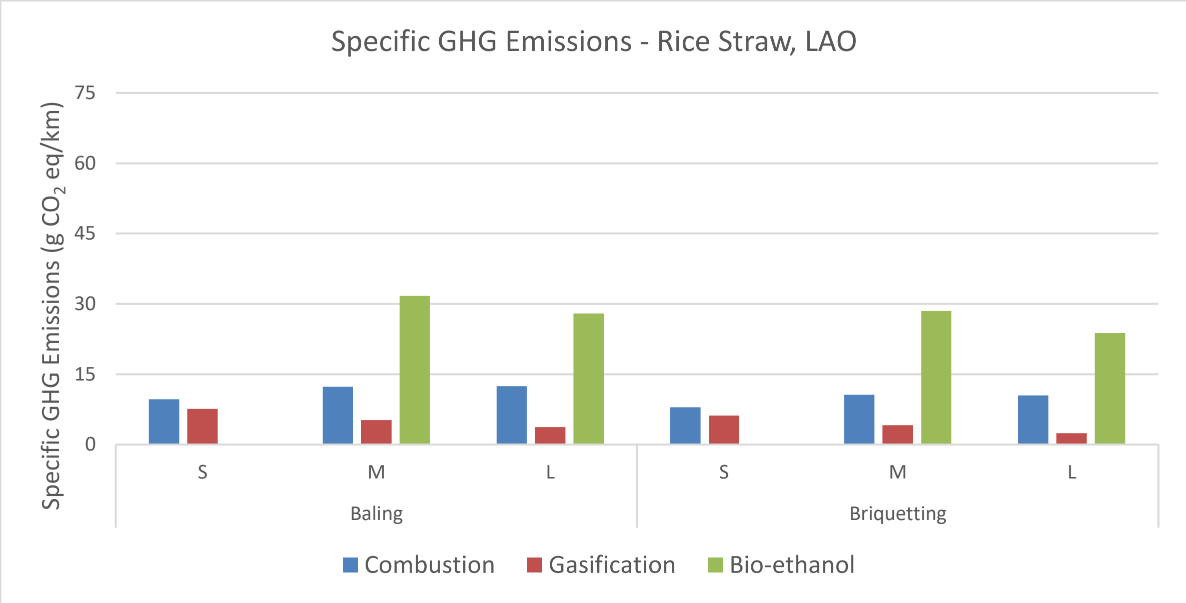

Figure 5.11: GHG emissions of energy recovery from rice straw in Laos for different Powerplant technology & sizes and densification techniques

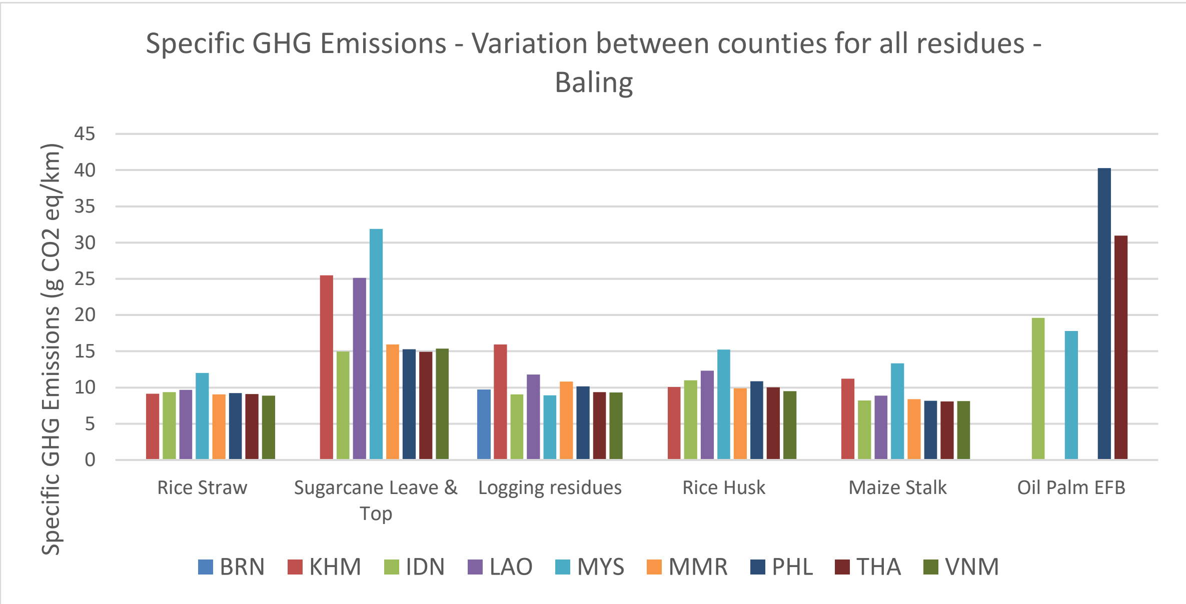

Figure 5.12: Specific GHG emissions of energy recovery from various countries for all the residues, for 1MW combustion powerplant with baling configuration

Figure 5.11 shows the emissions of energy recovery from rice straw in Laos for various configurations. In comparison to Figure 5.8, we see that the emissions are lower, especially for the case of briquetting.

Figure 5.12 shows the variation in GHG emissions of energy recovery from different residues (for 1 MW Combustion powerplant with baling as the densification technique). The difference from one country to another in this case is mainly caused by changes in collection distances. Hence the difference is not great. However, for the case of briquetting, the difference is high as it involves GEF which is seen in Figure 5.13. The existing grid mixes have a great influence on the considered pathways.

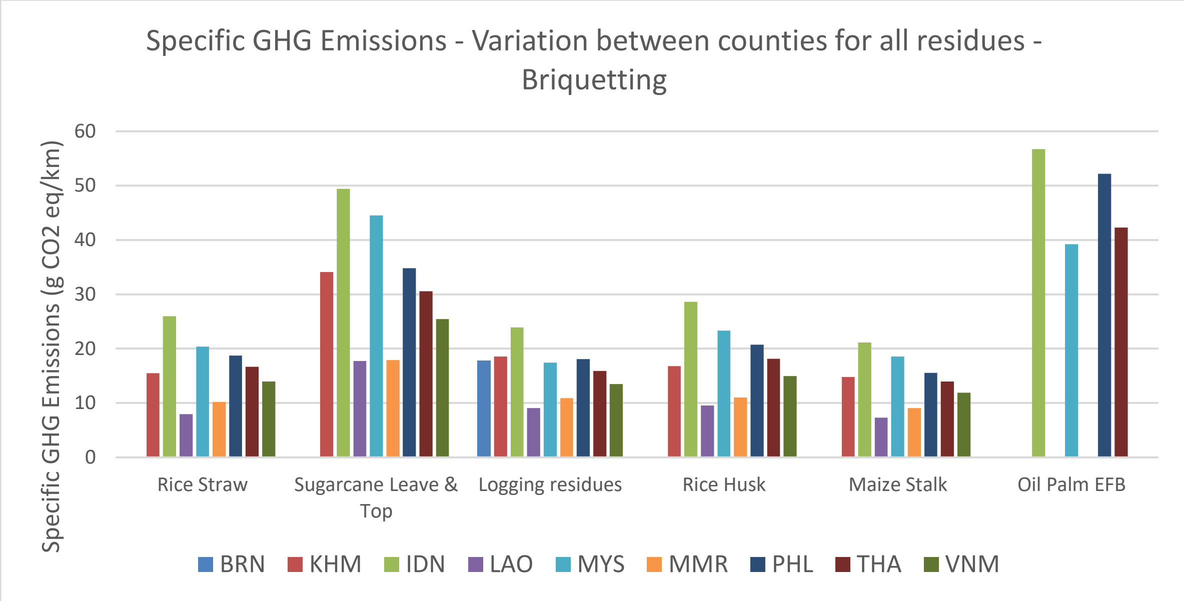

Figure 5.13: Specific GHG emissions of energy recovery from various countries for all the residues, for 1MW combustion powerplant with briquetting configuration

5.1.5.5 Impact of biomass densification

The influence of the biomass densification process on the emissions depends majorly on the grid emission factors. For countries such as Laos and Myanmar, whose GEFs for GHG emissions are low, briquetting proves to be advantageous. This can also be seen by comparing Figure 5.12 and Figure 5.13. For all the other countries, whose GEFs are higher due to high fossil fuel dependency, baling is preferred. The larger collection distance caused by bigger (centralised) powerplants does not seem to advantage briquetting greatly for the sizes under consideration. However, there are some minor anomalies found. Though Myanmar has low GEF, baling process is preferred for rice husk as the rice production is densely distributed. On the contrary, the sparse distribution of maize stalk in Cambodia prefers briquetting for bio-ethanol production (200 MW configuration).

5.1.6 Tank to wheel emissions of bio-energy recovery at national scale

The primary aim of this thesis is to evaluate the emission saving potential of the use of bio-energy in transport sector at a national level. Previously, the energy recovery pathways were evaluated by comparing them at the vehicle level. These results must be translated to be applied at national level. The methodology followed for the same is as follows.

The best pathway (i.e., the one with least GHG emissions) of electricity production of every residue type is identified by comparing all the configurations (i.e., different technology, capacities and processing method). The identified pathways for each crop are ordered from least emissive to most emissive (in terms of GHG emissions). The maximum producible electricity/ethanol is evaluated using the efficiency of the chosen technology and the biomass availability (as evaluated in Chapter 4). Then a merit order curve that represents the relationship between specific emissions (i.e., emissions per unit energy) and total recoverable energy is plotted. The same is repeated for bio-ethanol. A sample plot showing the relationship between amount of energy recovered and emissions for bio-electricity and bio-ethanol is shown in Figure 5.14 and Figure 5.15. Since only six major residues was considered the emissions of the other residues were evaluated based on the average of the six.

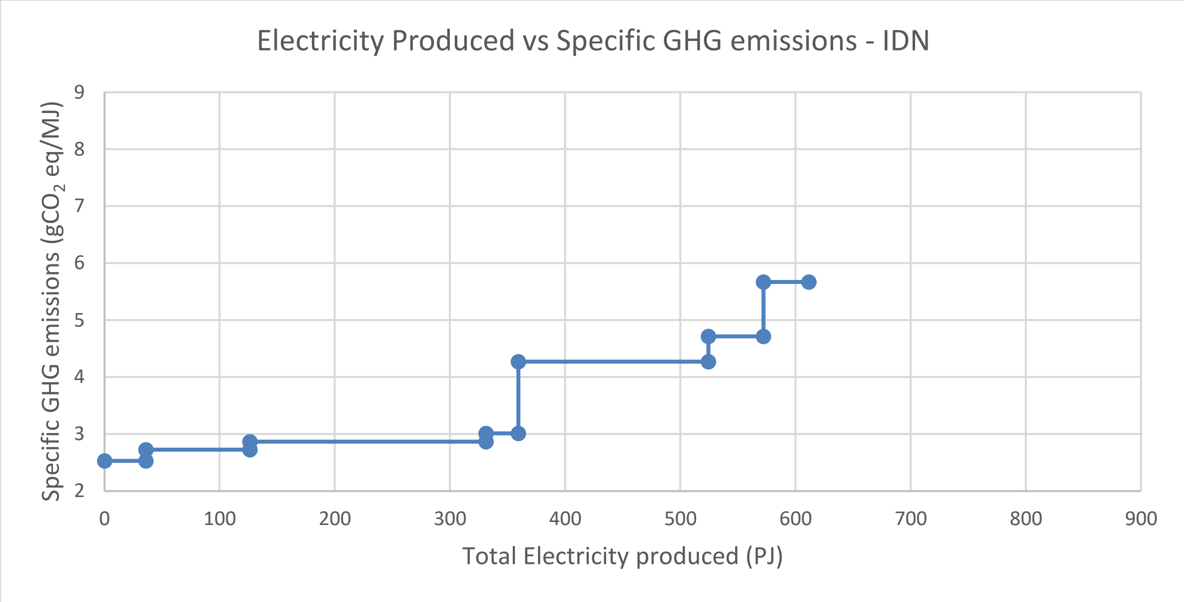

Figure 5.14: Merit order curve of emissions of bio-electricity production from biomass residues in Indonesia

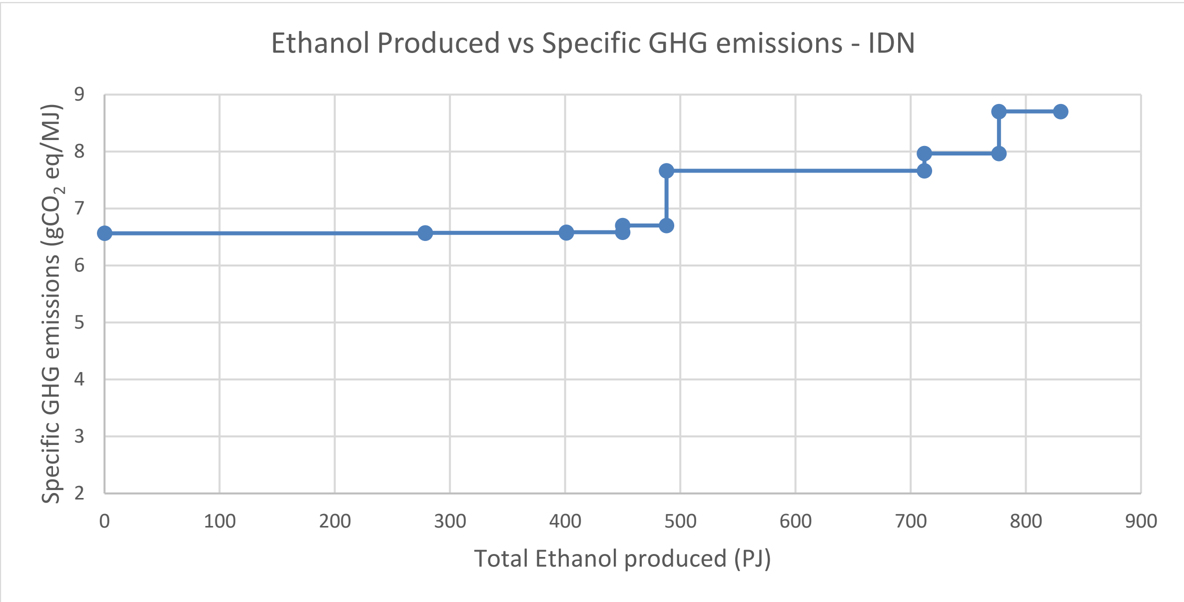

Figure 5.15: Merit order curve of emissions of bio-ethanol production from biomass residues in Indonesia

5.2 Estimation of bio-energy demand of an alternate fleet and potential supply scenario

5.2.1 Quantification of bio-energy requirements

As seen from chapter 3, the vehicle population mix in ASEAN for each country is very different. Similarly, the availably of bio-energy as seen from chapter 4 and the emissions of energy recovery as seen in earlier in this chapter varies widely for each country. Hence to assess the replacement and emission mitigation potential of bio-energy in transport sector, we need to quantify the bio-ethanol and bio-electricity needs for the different countries of ASEAN. There is also a need to quantify the bio-energy needs at different levels of penetration to make sure we can match the demand with availability in order to evaluate the maximum emission mitigation potential, and to assess various scenarios. The approach for ethanol and electricity is different and has been dealt with separately in the following sections.

5.2.1.1 Quantification of Bio-ethanol needs

Bio-ethanol has fuel properties like that of petrol. It can be used in transport sector through petrol engine (i.e., spark ignition) vehicles. They are not able to replace the demands of the diesel vehicles, as they cannot be used in diesel engines directly. Hence, it was opted to evaluate different levels of bio-ethanol penetrations by varying the petrol ethanol blend (and not by replacing an entire vehicle type, e.g., passenger car).

5.2.1.1.1 Common ethanol blends

Ethanol fuel mixtures are prefixed by 'E' which denotes the percentage of anhydrous ethanol in the mixture by volume. For example, E5 blend corresponds to a blend of 5% ethanol and 95% gasoline blended on a volume (v/v) basis. The volumetric energy density of ethanol is lower than that of petrol. Typically, a litre of petrol is equivalent to 1.5 litre of ethanol on energy basis. A few countries already use different level of ethanol in their gasoline. The common ethanol fuel mixes used in practise are, E5, E10, E25, E 85 and E 100. E5 is used in many parts of western Europe today and is catching up in countries like Argentina, Canada and India. E10 is used in many parts of the USA. It is also predicted that western Europe would increase ethanol blends to E10 in near future. Brazil, the forerunners in bio-ethanol use E25 blends. They use the higher blends, i.e., E85 and E100 through flex fuel vehicles. Hence these 5 common blends mentioned above shall be the ones considered in our study.

5.2.1.1.2 Vehicle/Engine Modifications required

Though bio-ethanol can be used in petrol engines, their density and viscosity are not the same. Hence there are some modifications required in the existing vehicle, for it to be able to take different blends. Very low blends i.e., E5 require no modifications at all. For E5-E10 blends, the existing vehicles shall be able to use it with minor modifications to the carburettor. For using higher blends, i.e., E10-E85 some major modifications to carburettor, fuel pump, fuel filter, ignition system, etc. However, this could be achieved by retrofitting. But for blends higher than 85%, specially designed vehicles with engines that can run on pure ethanol alone are required. Figure 5.16 and shows the modifications in the vehicles/engines that are necessary for different ethanol – petrol blends [225]. As discussed previously, the emissions involved in the production of infrastructure is left out of the scope of this work. Hence the emissions associated with vehicle modifications, retrofitting and production of new vehicles is left out of the scope of this work.

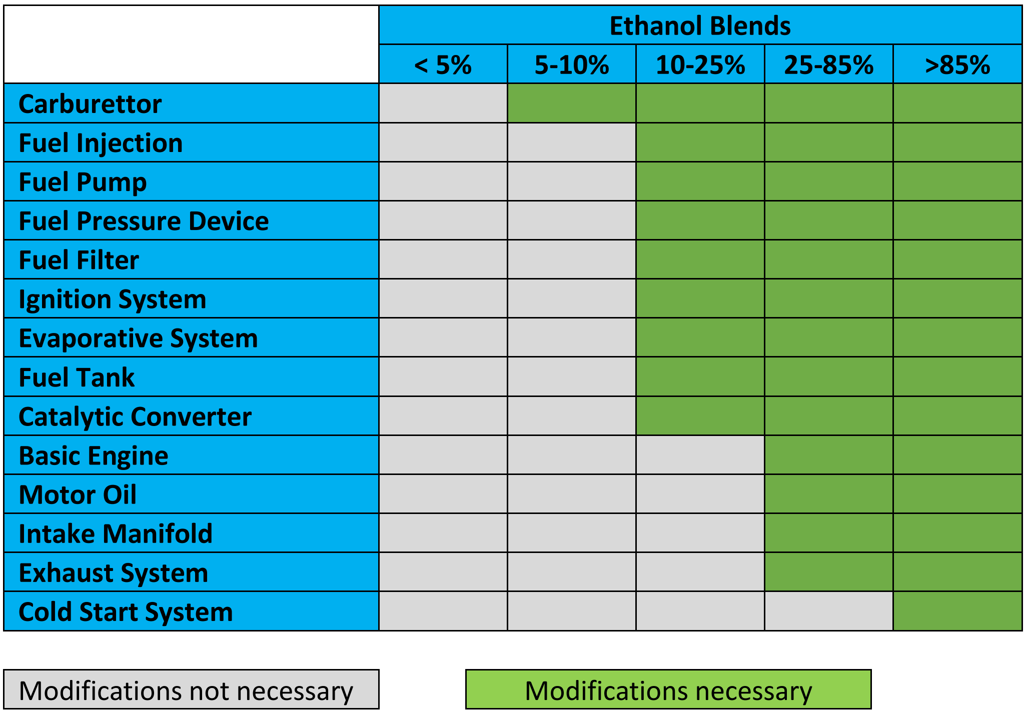

Figure 5.16: The necessary modifications to be done in an engine for different petrol ethanol blends

5.2.1.1.3 Methodology

COPERT, is the software of choice for the evaluation of energy demand and emissions from vehicle at a national level as described in chapter 3. It can give us the emissions and energy needs for different bio-ethanol blends, viz. 5%, 10%, 70%, 85% and 100% at national level directly. Hence by modifying the fuel blends in COPERT, the energy and emissions of vehicles for E5, E10, E25, E85 and E100 fuel blends are found. COPERT separates the carbon emissions from a blend vehicle into biogenic and fossil i.e., it assumes the carbon content of the ethanol to be of biogenic origin. This suits well with the description made in our evaluation regarding carbon neutrality. The CO_2 emissions of biogenic origin is assumed to have no GWP.

5.2.1.1.4 Results

Figure 5.17 shows the demand of bio-ethanol for different fuel mixes in the ASEAN countries. The ethanol need is directly related to the petrol consumption in a country, which further depends on its vehicle types. In general ASEAN has a higher use percentage of petrol over diesel. As seen from chapter 3, 53% of all the transport energy needs in ASEAN comes from petrol. Malaysia (79%), Cambodia (63%), Vietnam (61%), and Indonesia (55%) have the highest ratios of energy coming from Petrol. The higher usage of MCs and petrol PCs contribute the higher petrol usage. Hence ASEAN could benefit largely from use of bio-ethanol.

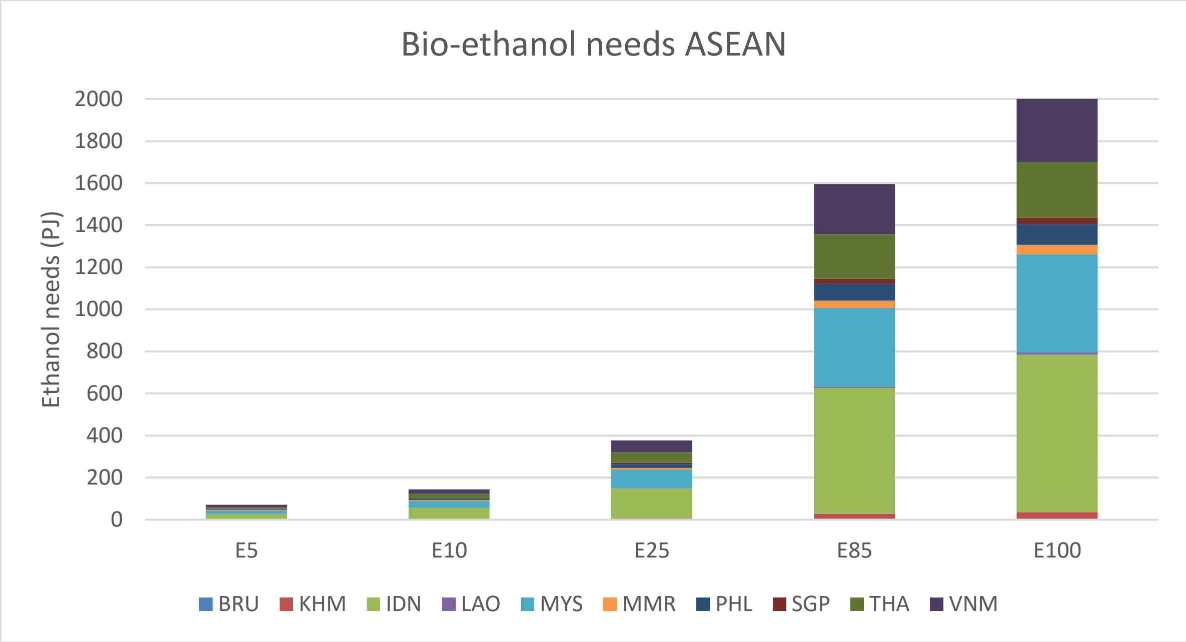

Figure 5.17: Bio-ethanol needs in different ASEAN countries

5.2.1.2 Quantification of bio-electricity needs

The bio-electricity produced from biomass residues could be used in transport sector through electric vehicles. While bio-ethanol can be used in existing vehicles (at lower levels) as a fuel blend, electric vehicles require new electric vehicles for their implementation. Hence, for analysing various levels of bio-electricity use, we will consider replacement of an entire vehicle type (such as cars, buses, etc.). This is different from the ethanol blends approach used for bio-ethanol.

5.2.1.2.1 Methodology

The methodology followed for evaluation of TTW energy needs and emissions of electric vehicles is a simplified one. The electric vehicles produce zero tailpipe emissions and hence their TTW emissions are taken to be zero. The per annum energy needs of the different vehicles at national level are evaluated by multiplying the specific energy consumption of the vehicle (MJ/km) type with the stock and activity (VKT) data. The specific energy consumption of an electric vehicle depends on many factors such as driving speeds, conditions, driving patterns, vehicle loads, etc. Unfortunately, a large database on energy consumption of electric vehicles (such as COPERT for conventional vehicles) is not available. For evaluating energy using longitudinal dynamics model, driving patterns are necessary, which is not available either. Hence a single value that represents energy consumption of a vehicle type is taken from literature after careful considerations. Vehicle classes are considered wherever possible. Electrified trucks are left out of the scope of this evaluation. Similarly, Medium and large category MCs are not included as well. Table 5.9 provides the TTW specific energy needs of the different vehicle types obtained from different sources [36], [52], [69].

Vehicle type	Vehicle class	Specific energy (MJ/km)
PC	Mini	0.72
	Small	0.89
	Medium	1.02
	Large	1.07
LCV	--	1.08
Buses	<15t	2.88
	15-18t	3.60
	>18t	4.32
MC	Small	0.288

Table 5.9: Specific energy consumption of electric vehicles

5.2.1.2.2 Results

Figure 5.18 gives the electricity demand needed for the electrification of different vehicle types in ASEAN nations. The total energy requirement is as low as 2.8 PJ (0.8 TWh) for Brunei to as high as 299.3 PJ (83.1 TWh) for Indonesia. The energy needs are directly proportional to the vehicle population. Hence the electricity requirement pattern is very similar to the fossil energy requirement. To just understand the scale of electricity required for transport electrification, a comparison to national electricity production can be made. It is seen that the demand of a fully electrified transport can be as low as 12% of electricity generated for Singapore and as high as 45% for Cambodia. Hence complete electrification of road transport in ASEAN would have a considerable impact on the grid.

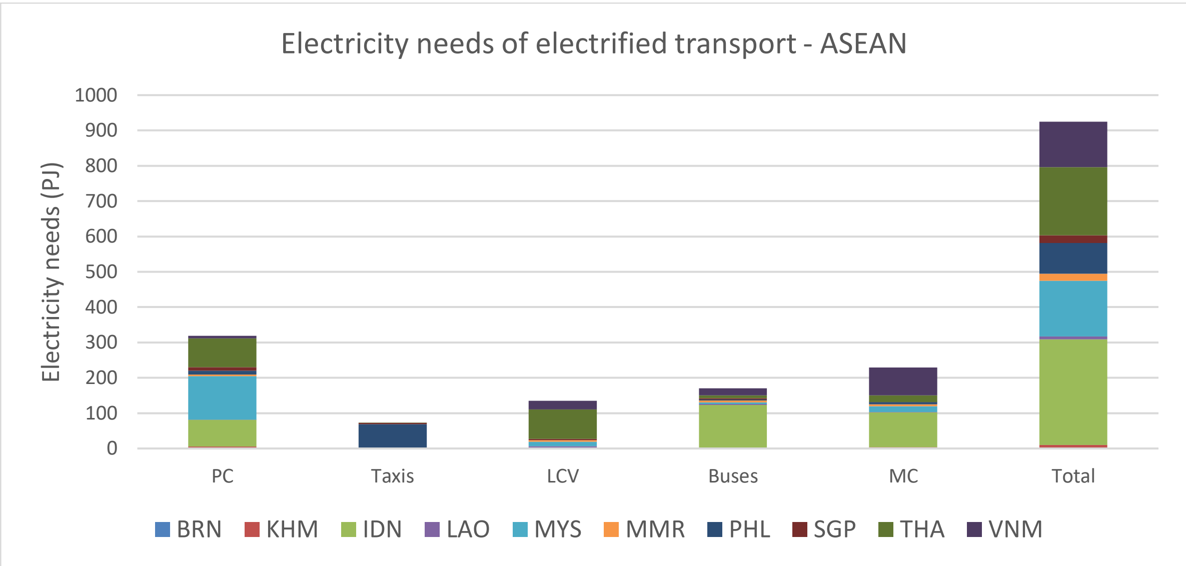

Figure 5.18: Electricity demand of electrified transport in ASEAN countries

5.2.2 The different plausible replacement scenarios

In section 5.1.6 we estimated the emissions of energy recovery for the different amounts of energy recovery. One of the outputs of this study was also the maximum amount of energy that can be recovered from biomass residues in each country. This maximum energy evaluated accounts for the biggest powerplant technology possible, minimum residue availability for powerplant operation, residue availability in each island, etc. Table 5.10 and Table 5.11 shows the energy demands for various scenarios of electrification and bio-ethanol usage and compares it with the maximum amount of bio-electricity and bio-ethanol production respectively for each country.

	Energy needs (PJ)						Energy producible (PJ)
	PC	Taxis	LCV	Buses	MC	Total	
BRN	2.3	0.0	0.1	0.4	0.0	2.8	0.2
KHM	2.9	0.0	0.0	0.5	3.7	7.1	40.4
IDN	75.9	0.0	2.8	122.3	98.2	299.3	611.6
LAO	0.3	0.0	3.5	2.9	0.9	7.6	20.2
MYS	122.7	0.9	12.9	4.4	16.4	157.3	101.7
MMR	5.3	0.0	4.6	4.9	5.5	20.4	141.4
PHL	10.2	67.6	0.0	3.2	6.4	87.3	177.7
SGP	10.6	3.5	3.1	3.9	0.4	21.5	0.1
THA	81.3	0.1	84.0	8.2	18.8	192.5	288.7
VNM	7.6	0.0	23.8	19.3	78.8	129.4	228.8

Table 5.10: Comparison of bio-electricity needs and availability

	Energy needs (PJ)					Energy producible (PJ)
	E5	E10	E25	E85	E100	
BRN	0.2	0.4	1.1	4.7	5.9	0.0
KHM	1.1	2.2	5.7	24.2	30.3	53.5
IDN	26.5	53.7	141.0	597.0	748.2	830.4
LAO	0.4	0.7	1.9	8.1	10.1	25.1
MYS	16.5	33.5	88.0	372.6	467.0	137.1
MMR	1.6	3.2	8.4	35.5	44.5	190.5
PHL	3.5	7.1	18.6	78.8	98.8	241.1
SGP	1.1	2.2	5.8	24.6	30.8	0.0
THA	9.4	19.1	50.0	211.7	265.3	392.0
VNM	10.6	21.5	56.4	238.8	299.3	310.6

Table 5.11: Comparison of bio-ethanol needs and availability

By comparing the energy demands and supplies, the possible scenarios are identified. Most of the ASEAN countries (except Brunei, Malaysia and Singapore) can satisfy the entire bio-energy needs for all the scenarios. The satiable demands have been highlighted in green in the above tables. The bio-energy production in Brunei is too low to supply most of the energy most of transport sectors demands. Only the energy needs of MCs and LCVs can be satiated. Hence it is assumed that bio-energy is not used in transport sector of Brunei. Similarly, Singapore does not produce enough biomass residues to power any portion of its energy needs. It is to be noted that horticultural residues and MSW is not considered in this thesis. One may refer to this publication to identify the bio-resources available within Singapore [226]. For Malaysia, only partial needs of the transport sector can be satisfied, owing to very high energy demands of transport sector and low bio-energy availability.

5.3 Emission saving potential of use of bio-energy in transport sector – Results

The WTW emissions of the conventional vehicle fleet, i.e., the baseline emissions have been established in chapter 3. Combining the total bio-energy availability (Chapter 4) and the emissions of bio-energy recovery pathways (earlier in this chapter), the merit order of emissions of energy recovery is plotted. The bio-energy needs for different replacement scenarios is evaluated in section 5.2.2. Combining the three results, the WTW GHG emissions for different bio-electricity and bio-ethanol scenario is evaluated.

5.3.1 Bio-electricity

Figure 5.19 shows the WTW GHG emissions caused by electrification of road transport in ASEAN using bio-electricity, for different scenario. Scenario 'none' represents the case where no vehicles are replaced, and all represents the one in which all vehicles are replaced. It can be very evidently seen that the use of bio-electricity in transport sector can cause huge reduction in overall GHG emissions. The overall emissions reduction that can be achieved in ASEAN is 72%. This number varies from one country to another. Singapore and Brunei do not offer any reduction at all due to lack of bio resources. Malaysia enjoys only a 21% reduction in emissions, as their energy demand is high whilst their bio-energy supply is low. Of the countries which can satiate 100% of its bio-electricity needs from the locally available bio residues, Indonesia performs the best (91% reduction) and Cambodia performs the least (75% reduction). In terms of absolute numbers, Indonesia, Thailand and Vietnam offers the most savings.

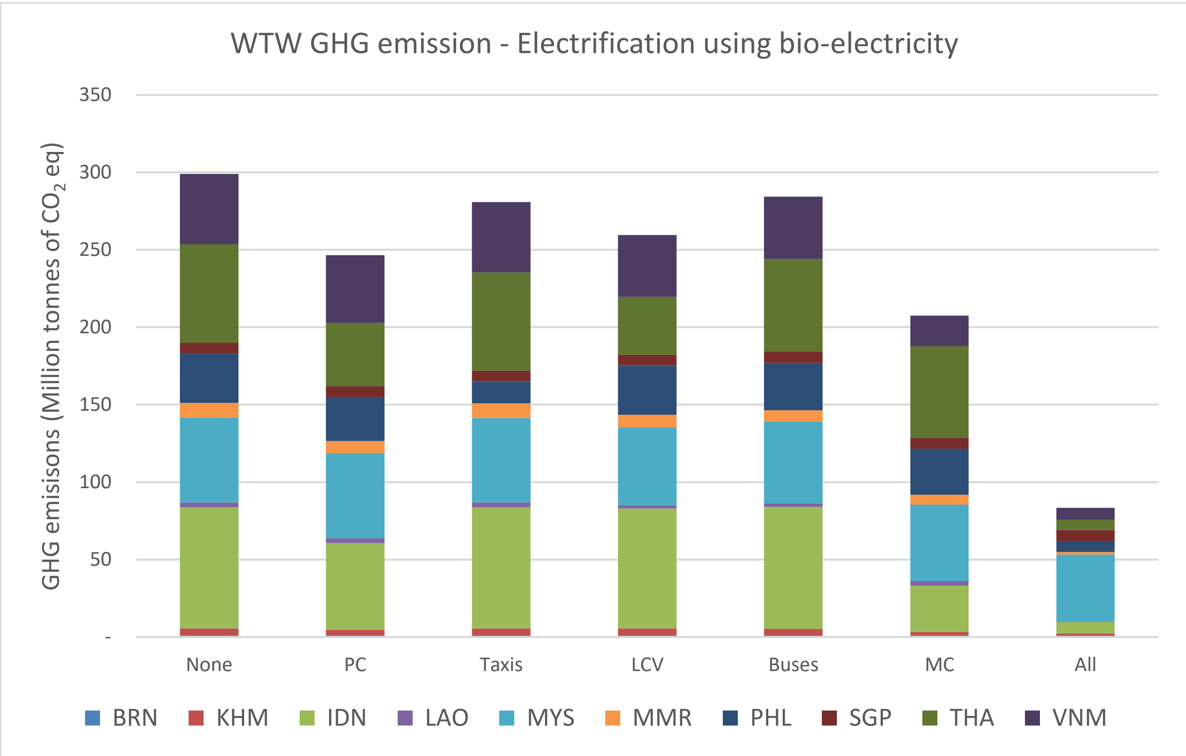

Figure 5.19: WTW GHG emissions of different scenarios of electrification using bio-electricity in ASEAN

Regarding the different scenarios, it can be seen the electrification of MCs provides the maximum benefit followed by PCs and LCVs (31%, 18% and 13% respectively). These numbers represent entire ASEAN and the situation could be different for each country based on its vehicle population mix. For instance, in Laos, replacement of LCVs, Buses and MCs, cause the most reduction in emissions (38%, 36% and 7% respectively). Whereas in Thailand, the most reduction would arise from the replacement of LCVs, PCs and MCs (41%, 12% and 12% respectively).

One needs to keep in mind that this evaluation does not include costs of replacement. For instance, replacing one taxi with a much higher utilisation (VKT) can provide the same emission saving that replacement of 10 cars would provide. Similarly, the emissions involved with provision of infrastructure is also not included. Hence a more detailed analysis which included the above-mentioned aspects is needed to draw strong conclusions, which can be done in future works.

5.3.2 Bio-ethanol

Figure 5.20 shows the WTW GHG emissions caused using different blends of bio-ethanol derived from biomass residues in road transport in ASEAN. It is seen that the use of bio-ethanol in transport in ASEAN can cause huge savings in emissions. The savings range from 2% for the E5 scenario to 43% for the E100 scenario. The saving of emissions varies from one country to another. Brunei and Singapore with no bio resources are unable to enjoy any savings in emissions. Malaysia, even with only partial replacement (E25) can reduce up to 40% of their emissions. Of the countries that can satisfy the entire demand for E100 scenario, Cambodia offers maximum savings of 58% while Philippines offers the least savings of 24%. Apart from the differences in the upstream emissions of bio-ethanol production, the fuel mix of each country has a big impact on emission saving potential. This is because, bio-ethanol can only replace the petrol part of the transport energy needs. In terms of the absolute emission savings, Indonesia is poised the best followed by Vietnam and Thailand (62.5, 25.7 and 22.5 million tonnes CO_2 eq respectively).

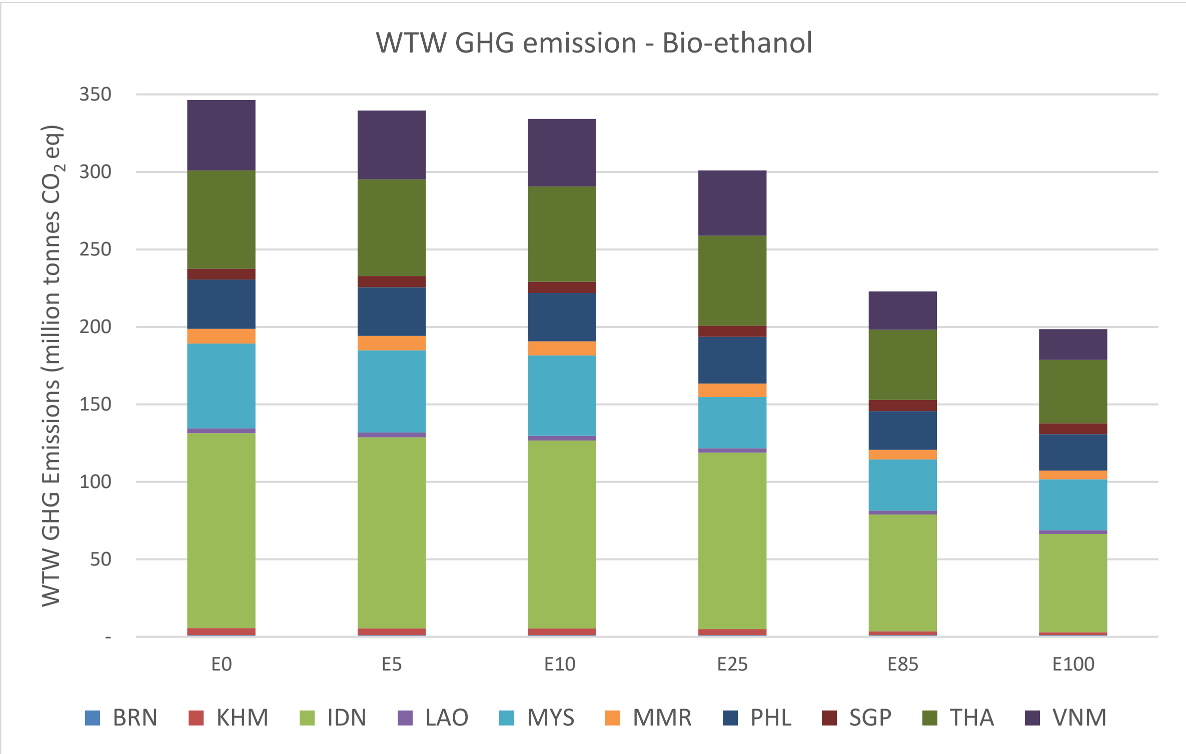

Figure 5.20: WTW-GHG emissions for different ethanol blends in ASEAN

5.3.3 Comparison of bio-electricity and bio-ethanol

Comparing the maximum emission saving potential of bio-electricity and bio-ethanol, bio-electricity offers more savings. There are many reasons for the same. As seen before, bio-electricity production is innately a less emissive process as compared to bio-ethanol. The vehicles can use the bio-energy produced at higher efficiencies. Also, in the scenarios considered, bio-electricity can replace all vehicles except trucks. Bio-ethanol however can replace only the petrol portion of the transport energy demand. However, the infrastructural demands required for electrification is more complicated than for bio-ethanol, and it require new vehicles. Also, in future, ethanol reformate fuel cells and direct ethanol fuel cells could use the bio-ethanol at higher efficiencies.

5.3.4 Comparison to electric vehicles driven by grid

As seen in chapter 2, the emission of an electric vehicle depends on the source of electricity production. In this section, an electric car (medium sized passenger car) is compared to petrol and diesel car (of the same size). Figure 5.21 shows the comparison of GHG emissions of conventional vehicle and EVs driven by different energy mixes. The same graphs for acidic gases and particulate matter could be found in the appendix (Figure A.8 and Figure A.9).

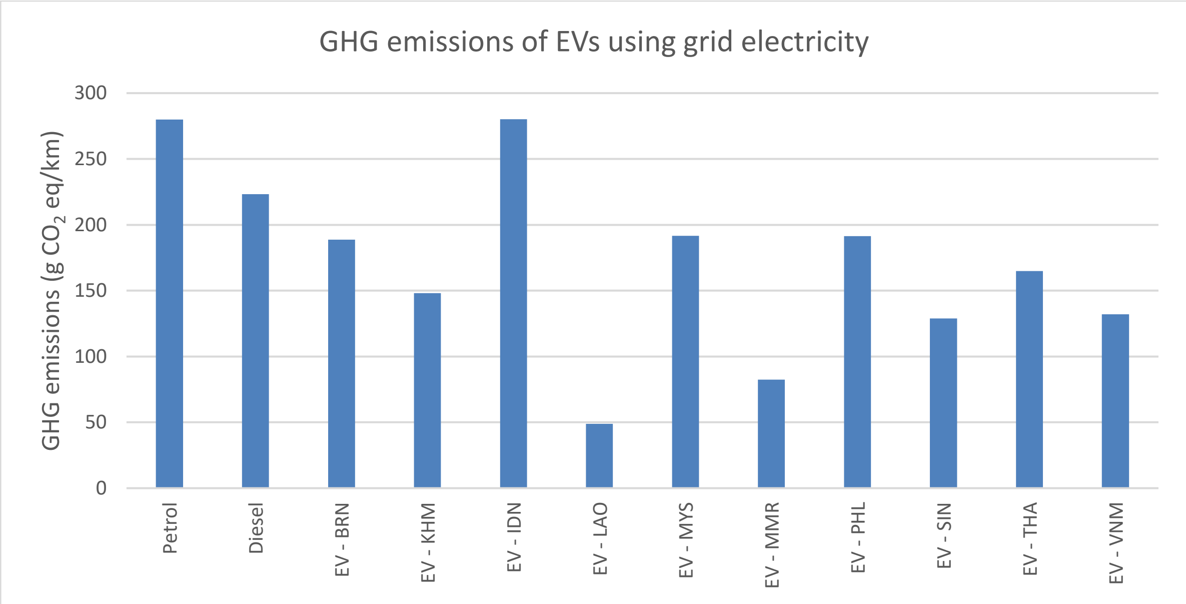

Figure 5.21: GHG emissions of a mid-size passenger car using grid electricity for different ASEAN countries

Barring Indonesia, the WTW GHG emissions of EV (for all countries) is lower than conventional petrol and diesel cars. The emission reduction potential of electric vehicles varies widely from one country to another. Laos, which derives most of its energy from hydro power can benefits the most, with reduction potential ranging from 78 - 83%. Indonesia lies in other end of the spectrum, with the emissions being almost the same as a petrol car and even higher than a diesel car. This is due to its high dependence on fossil fuels, especially lignite. This also causes high emission of PM and acidic gases (refer appendix Figure A.8 and Figure A.9). An EV driven by the grid mix of Indonesia produces 35 times as much as PM as compared to a petrol car. Singapore, however, presents a slightly different case. Though its almost 100% fossil fuel dependant, because it derives most of its energy from NG-IGCC, an EV can save 42-54% of emissions compared to conventional vehicles. Even the emissions of PM and acidic gases are lower than conventional vehicles. This reiterates the importance of transition to renewable electricity, if full benefits of transport electrification are to be realised. Now that the impact of grid mixes on individual vehicle is discussed, the impact of electrification of entire transport fleet can be analysed. Figure 5.22 below indicates the impact of maximum electrification in all the ASEAN countries, if the entire fleet was electrified by their respective grid mixes. For aggregated

ASEAN, electrification of MC offers the biggest emission reduction potential (of 13%) followed by PCs at 8%.

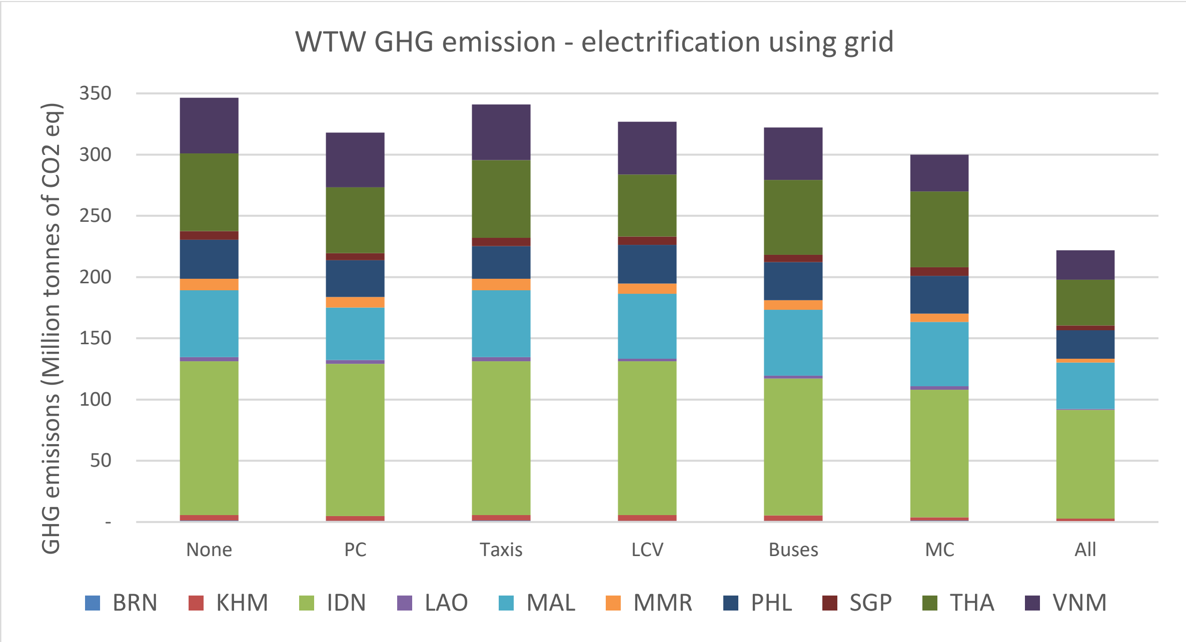

Figure 5.22: WTW GHG emissions of transport electrification in ASEAN using Grid Electricity

The ASEAN wide emission reduction is only 36%. On the other hand, bio-electricity scenario can offer reduction of up to 72%. Even bio-ethanol, which replaces only the petrol can offer reduction of up to 43%. Hence the use of bio-energy in transport sector is more advantageous than electrification using the existing grid electricity.

6 Discussion

In the first section of this chapter there will be a discussion on the results that were attained in the previous chapters and the different findings of the thesis shall be brought together. Then there will be a section that highlights the key findings of the thesis.

The main aim of the thesis was to find out the emission mitigation potential of use of bio-energy in transport sector of ASEAN. This was broken down into a few sub questions. A database of vehicles in ASEAN was developed and their emissions & energy consumptions were estimated. The total biomass residue availability in ASEAN was estimated and their potential locations were identified. The different bio-energy products to be produced from the biomass residues that can be used in the transport are identified to be bio-ethanol and bio-electricity. Their pathways of production were established, and the emissions of energy recovery from every individual pathway was evaluated. The impact of decentralisation and different densification techniques were studied as well. The total bio-ethanol and bio-electricity that could be produced from the available biomass residues was estimated and their emissions of energy recovery were calculated. The bio-electricity and bio-energy demands for ASEANs transport sector (for different levels of bio-energy penetration) were estimated. The demand and supply scenarios were matched. And finally, the main question 'What is the emission saving potential of use of bio-energy derived from biomass residues in ASEAN's transport sector?' was answered.

6.1 Discussion

This section brings together the different findings from the different sections of the Thesis and discusses the same. As seen before, transport sector is a major contributor of emissions globally and plays an even bigger part in the case of Southeast Asia. Road transport forms the biggest share of transport emissions and in ASEAN, it is about 92% of all the transport related emissions. With most of the ASEAN countries in developing status this is going to increase further rapidly and hence needs immediate mitigation. As observed previously, electricity, hydrogen and bio-fuels are the main low carbon alternatives available. However, an initial evaluation suggested that hydrogen might not provide a long-term sustainable alternative considering its carbon footprint (when produced from fossil sources) and lack of ability to include renewable energy (with good efficiency). Hence hydrogen was left outside the scope. Electric vehicles are the other obvious choice. However, it was observed that the energy mix of electricity generation has a major impact on the emissions of electric vehicles. Most of South East Asian nations (barring KHM, LAO and MMR) rely heavily on fossil fuels for their electricity production. Especially the usage of coal and lignite which produce high GHG emissions per unit electricity produced is very high in countries like IDN, PHL and MYS, etc. Natural Gas also plays a major role in most ASEAN country's electricity generation. Hence, electrification of vehicles need not be the right way forward, especially if the grid mix is to remain the same. In the initial assessment of the alternatives, the option of biofuels especially if derived from biomass residues seemed to provide a low carbon sustainable alternative. With most of ASEAN country's economy largely depending on agriculture, they could possess a sizeable quantity of bio residues. With this background, this thesis set out to assess the emission mitigation potential of use of bio energy in ASEAN's road transport sector.

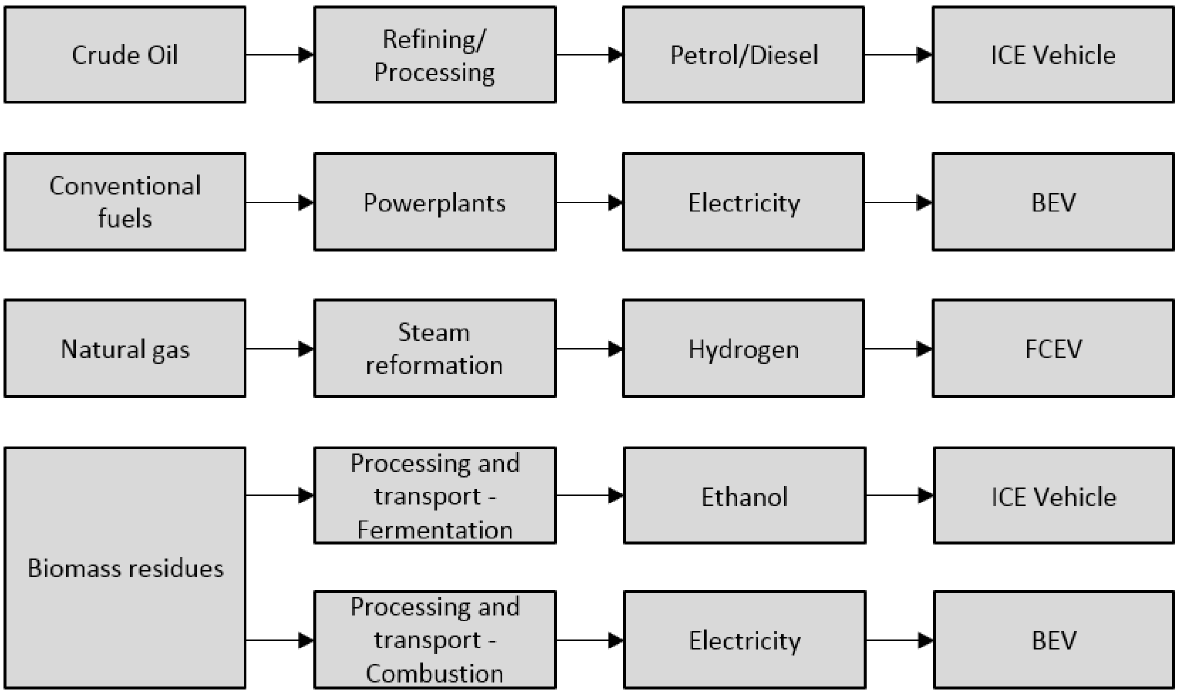

Figure 6.1: Well to wheel pathways of conventional and alternative transport

For evaluating the emission mitigation potential of use of bio-energy in transport, it is essential to estimate the emissions of existing fleet in ASEAN. This assessment started with a literature survey on the existing emission estimation models. As a common model was not available for the 10 different nations under consideration, a methodology was established to evaluate the same. The model built was validated based on the statistical fuel consumption available from government websites. Some interesting trends were observed. The largest country (by land area and population) Indonesia produced the highest amount of GHG emissions. However, the per capita emission of other countries depended lot on their level of development. For instance, though Thailand was not the second largest or populated country, its emission levels were high. On the contrary Cambodia, Myanmar and Laos have very low per capita emissions as they are still in developing or underdeveloped state. Vehicle ownership is rather low in these countries. This gives them an opportunity to include low carbon options in their growing vehicle mix and they should consider these options in their development plan, if they desire to have a low carbon future. The more developed nations of Singapore, Brunei, Malaysia, etc. have passenger cars as their single largest emitters. Along with efforts to decarbonise the PCs, efforts to increase the share of public transportation might provide beneficial results. Overall (ASEAN), PCs dominate the emission sector. However, the profile of emission varies from one country to another. Vietnam, Myanmar and Cambodia have a large share of MCs (petrol driven). Finding alternatives for MCs could help these countries achieve reduction targets more easily.

In the next step, the biomass potential (from residues) in Southeast Asia was analysed. Since a common study for all 10 ASEAN countries following the same methodology was not available, an indigenous methodology had to be developed. In addition to that the location of the residues had to be identified to enable the identification of transport distances for biomass collection. An extensive data mining was done and using the land use patterns, the potential locations were identified. The bio-energy potential (from residues) was mapped at a very detailed level for the entire ASEAN which is nowhere to be found in literature. The total residue availability in ASEAN is estimated to about 1089 TWh with Indonesia contributing to about 38% of it. Residues from Agriculture (86%) and Forestry (10%) form the biggest chunk of available energy. The potential of livestock is minimal and hence it would be prudent of governments to focus on Agricultural and Forest residues. It is also observed that high density of biomass residues is available close to highly populated areas of Java, around Hanoi, Ho Chi Minh City, Yangon, Manila and east coast of Peninsular Malaysia. High biomass residue density could also be found along the major riverbanks, which are also densely populated. The high-density population areas are characterised by higher transport energy demand and hence the location of biomass residues is favourable. Though 26 different residue types were identified, six of them (rice straw, sugar cane trash, log residues, rice husk, Maize stalk and Oil Palm EFB) accounted for three fourth of all the residues. Hence the government and policy makers can focus on these residues, especially rice straw which accounts for 38% of all the residues available in ASEAN. In this study however, MSW has not been included. While the contribution from MSW might not be high at a country level, there might be significant contribution in a few cities with high population densities such as Jakarta, Bangkok, Ho Chi Minh City, etc. This could be included as a part of future work. The energy products that are producible from the biomass residue available in ASEAN, that would suit the transport sectors energy needs were identified to be bio-electricity and bio-ethanol. Owing to factors like technological maturity, suitability of feedstock, fermentation (ethanol), direct combustion and gasification were chosen to be the technologies.

In the next step, the emission of energy recovery from the biomass residues is estimated. As biomass (especially from residues) is associated with large collection radius and low volumetric densities, the impact of centralisation/decentralisation and biomass densification is studied as well. LCA is used to estimate the emissions. Comparing ethanol and electricity based on energy alone is not right. Hence a normal functional unit was defined to be 'a km driven by a mid-sized passenger car'. It was identified that both bio-electricity and bio-ethanol, when recovered from biomass residues performed environmentally better than the conventional options. Hence, they have a high emission saving potential. Gasification of biomass to produce electricity has the least emissions. The higher efficiency of ethanol production is compensated by the lower efficiency of the IC engines (as compared to a BEV). Nevertheless, the emission saving potential of bio-ethanol pathways are quite high as well. Also, in the future if technologies such as ethanol reformer-based fuel cell vehicles or direct ethanol fuel cell vehicle are commercialised, they might be able to consume the ethanol at a higher efficiency. This shall further improve the resource (bio-residues) utilisation and reduce the emissions of bio-ethanol use. Bio-ethanol offers the additional advantage of immediate use in smaller ratios and hence can help in a smoother transition into bio-energy. Bio-ethanol cannot be eliminated just on the basis that bio-electricity offers higher emission reduction. It also needs to be understood that the emissions of vehicle manufacturing and infrastructural needs are not included in this study.

It is observed that the centralisation of energy recovery is advantageous in terms of both emissions and total energy recovered. This is primarily linked to the increased efficiency of a larger power plant. For instance, for direct combustion, a 50 MW powerplant is twice as efficient as a 1 MW powerplant. The emissions of biomass transport do not play a great role in the life cycle emissions of energy recovery. This also means that the location of the powerplant is not too critical in terms of emission reduction. This gives the flexibility for planners to choose the location of a biomass powerplant. Also, immaterial of the type of powerplant, the results suggest that the governments and policy makers should opt for higher efficient powerplants as opposed to trying to decentralise them. However, a larger centralised powerplant might need many trucks to arrive simultaneously, especially during the post-harvest period. Thus, the logistics and handling could pose a challenge as it could cause traffic jams if it is not managed properly. While time-series has not been considered in the Thesis, it could play an important part of planning and hence needs to be considered by policy makers.

The impact that densification of biomass prior to transport can have on overall emissions was analysed. The general trend observed is that the additional densification achieved through briquetting is not benefitting the reduction of transport emissions. The densification provided by baling seems to be enough for most country and crop types. The primary reason for this is that baling is powered by diesel, whereas briquetting is done using electricity. As we have observed before, the high fossil fuel penetration in ASEAN causes a greater specific emissions of electricity production. Hence briquetting is a carbon intensive process in most ASEAN countries (except Laos and Myanmar). Even the long transport distance needs for centralised powerplants do not favour briquetting. This reiterates the importance of decarbonising the grid. It has a compounded impact on many other energy related processes. Countries that focus on reducing their carbon footprint might benefit a lot if they start off with decarbonising their grid. This analysis of densification of biomass has been focussed on emissions only. The cost assessment might give it a different perspective. The reduction in transport cost could outweigh the cost associated with upfront briquetting. This requires a detailed analysis.

Another keen observation from the results suggest that the variation of emission for the same crop type across different countries is not huge if baling is considered. The slight variation is caused by the difference in distribution densities, which does not vary much between the countries. However, if briquetting is considered, the variations are high as the GEFs between the countries are quite high. The difference between emissions of energy recovery from different residue type for the same country is quite high. It is highly influenced by the energy content of the residue and their spatial distribution which varies quite a bit between the crop types.

Using the results evaluated (i.e., emission of energy recovery of the different pathways, for different biomass residues in different countries) a merit order curve of TTW emissions of bio-energy recovery was plotted. These curves plot the emissions of energy recovery against the total energy recovered for the for bio-ethanol and bio-electricity for all the ASEAN countries. Subsequently, the bio-electricity and bio-ethanol needs of ASEAN's transport sector for different levels of bio-energy penetration was evaluated. The scenarios for bio-electricity and bio-ethanol were different. Bio-ethanol was assumed to replace petrol vehicles through different blends (E5 to E 100). Bio-electricity was assumed to be used through electric vehicles. For assessing different levels of bio-electricity penetration an entire vehicle type (such as cars or busses) was assumed to be replaced. The bio-energy demand was then compared with the bio-energy supply. As predicted, Brunei and Singapore with their high transportation needs and low bio-energy supply cannot satiate any of their transport energy needs with bio-energy. Hence these countries must look for other alternatives or import bio-energy from other countries for decarbonising their transport sector. Malaysia is only partially able to cover the demand from transport with bio-energy. They are still able to use bio-ethanol up to E25 blends and electrify every vehicle group except passenger cars using bio-electricity. Myanmar is on the other end of the spectrum where it produces almost 4.3 times is maximum bio-ethanol needs and 6.9 times the bio-electricity demands. Laos Cambodia, Philippines and Indonesia also can produce excess quantities of bio-electricity and bio-ethanol. These countries could act as exporters of bio-energy. Developed countries that lack renewable energy resources could import bio-energy from the bio-energy laden countries. Both the importer and exporter could benefit bi-directionally through carbon credits. Also, unmindful of whether these are used for transport, production of low carbon electricity from biomass residues could greatly help reduce the GEF of countries like Indonesia and Philippines.

In the final phase, various sections evaluated thus far are combined to evaluate the emission saving potential of use of bio-energy at national level. Here the discussion is split into three parts, viz. grid electricity, bio-electricity and bio-ethanol.

Grid electricity:

Looking at ASEAN in entirety, this should be the least preferred option. The high fossil fuel penetration of the grid is the primary reason for the same. In entirety, the maximum saving they could offer is 36% only. Countries like Indonesia, Philippines and Malaysia would benefit the least from this option. Without decarbonising their grids, these countries should not electrify their vehicles. Laos and Myanmar present a different story. Their grids are dominated by hydro power and hence they have low carbon footprint. Thus, even in its present state, these countries opt for electric vehicles driven by grid electricity. Singapore and Brunei present a peculiar case as both the countries do not have other suitable alternatives. They could opt for electrification. Singapore would benefit more than Brunei as it is almost entirely powered by Natural Gas (the cleanest source for fossil fuel electricity). Electrifying the entire fleet of Singapore would help reduce the emissions by 43%. If governments decide to do partial electrification, they need to be careful in choosing the vehicle types. For instance, in Singapore, electrifying the entire PCs would reduce the emission by 17% and the electrification of buses would lessen the emissions only by 15%. However, the total number of buses in Singapore are 17098, whereas the total PCs are 614510. The same analysis could be applied to all the countries to identify the starting point of electrification. Nevertheless, most ASEAN countries should decarbonise their grids before starting to implement electric vehicles.

Bio-electricity:

In terms of emission reduction, bio-electricity provides the least emission alternative. The overall emission reduction achievable is evaluated to be 72% for ASEAN. Indonesia stands to benefit the most as expected. The high efficiency centralised gasification of biomass (to produce electricity) and the very efficient electric vehicles can utilise the bio-residues in the best manner and produce least emissions. Many countries can provide all of it's transport's bio-electricity needs presently and will be able to do it for the future scenario as well. However, this is a well to wheel analysis which does not include the emissions of vehicle manufacturing and charging infrastructure. While the other alternative (viz. bio-ethanol) could start using the bio residues with the existing infrastructure, bio-electricity calls for new vehicles and infrastructure which deters its immediate implementation. The manufacturing of batteries is associated with high emissions as well. Also, this evaluation is focussed on GHG emissions only. An evaluation on PM, acidic gases and other emissions are required to make an informed decision. This alternative would also be involved with high capital costs for the vehicle and charging infrastructures, which would be a challenging task for the developing ASEAN nations. While bio-electricity perform best in absolute energy availability and potential emission saving, there are other aspects such as cost and infrastructural needs which need to be analysed before making a choice.

Bio-Ethanol:

The overall emission saving that bio-ethanol offers is around 43%. It is higher than what electrification with grid can provide, but lower than what bio-electricity offers. However, for bio-electricity, 5 out of 6 vehicle types are assumed to be replaced, whereas bio-ethanol is assumed to replace only the petrol fraction of the entire energy demand. Hence, they are not comparable in a strict sense. However, it is also true that the excess bio-electricity production (if all the residues are consumed) is higher than the excess bio-ethanol production in all the countries. But the biggest advantage that bio-ethanol offers over the other alternatives is its ease of implementation. It does not need new vehicles and charging infrastructure like electric vehicles which can lower the capital cost considerably. It allows for immediate implementation with lower blends such as E5 and E10 which directly reduces the emission by 2% and 4% at ASEAN level. With a few modifications, the E25 scenario can be implemented which provides saving of up to 13% at ASEAN level. Individual countries like Malaysia can save up to 40% of their emissions if they implements E25. Another interesting observation in ASEAN was the number of motorcycles they use. Motorcycles run entirely on petrol and can be easily adopted to use lower blends of ethanol. The government can also develop policies to implement flex fuel motorcycles which can run E100 fuel. This would help reduce a huge chunk of the emissions in many developing ASEAN countries. IC engines utilise bio-ethanol at low efficiencies. There is considerable amount of research focus on reformer-based fuel cells and direct ethanol fuel cells which are much more efficient than existing IC engines. Once a bio-ethanol economy is created, these technologies can be easily adopted in the future. Thus, though bio-ethanol saves lesser emissions than bio-electricity, it could offer a sustainable solution in terms of ease of implementation. It would offer a solution that has a smoother transition into a low carbon alternative.

6.2 Key findings

- The alternatives for road transport decarbonisation were identified and an initial evaluation was done.
- Alternatives that are most suited for the ASEAN were identified.
- The vehicle population for all the countries was established and further classified by vehicle type, size and fuel type.
- Energy demands of the existing vehicle fleet were evaluated and validated.
- Baseline emissions of existing conventional vehicle fleet was evaluated.
- Indonesia, Thailand and Malaysia produce the highest amounts of GHG emissions.
- The bio resources of relevance to this study were identified.
- The residues were quantified, and their locations were mapped.
- Indonesia, Thailand and Malaysia produced the highest quantity of residues.
- The critical resources were identified to be rice straw, sugarcane leaves and top, logging residues, rice husk, maize stalk and Oil Palm EFB.
- The bio-energy products that can be used in transport based on the residues available were identified to be bio-ethanol and bio-electricity.
- The pathways of energy recovery were identified.
- The impacts of centralisation of energy recovery and biomass densification techniques (baling and briquetting) on emissions is studied.

- The relationship between powerplant capacity and transportation distance was established for all the ASEAN countries using a map-based approach.
- In terms of emissions, centralisation (big centralised powerplants) was identified to perform the best for both bio-electricity and bio-ethanol.
- The higher efficiency of a centralised powerplant overcompensates the increase in transport emissions caused by bigger collection area.
- Baling performed better than briquetting for most countries, except Laos and Myanmar which have low GEFs.
- The reduction in transport emissions caused by briquetting does not compensate the emissions caused by briquetting itself.
- Gasification, owing to its higher efficiency and lower emissions is more preferred than direct combustion in terms of emissions.
- Both bio-electricity and bio-ethanol pathways offer high emission savings as compared to conventional fuels.
- Bio-electricity performs better than bio-ethanol for all the countries.
- The scenario of replacement of transport energy needs at national level is defined for bio-electricity and bio-ethanol.
- Bio-energy demands for various scenarios are estimated.
- Energy recovered vs emissions curve is plotted for bio-ethanol and bio-electricity for all the nations.
- The national level emissions savings of use of bio-energy in transport sector is evaluated.
- Bio-electricity can offer an emission saving of up to 72% for entire ASEAN.
- Indonesia, Thailand and Vietnam benefit the most in terms of both absolute and percentage reduction in emissions.
- Bio-ethanol can offer and emission reduction of up to 43% for entire ASEAN.
- Indonesia, Vietnam and Thailand benefit the most in terms of absolute emission reduction.
- Cambodia, Vietnam and Indonesia benefit the most in terms of percentage emission reduction.
- Electrification by grid in ASEAN does not seem to offer great emission reduction potential.
- Both bio-electricity and bio-ethanol perform better than transport electrification using grid electricity in terms of emissions.

7 Outlook

The outlook chapter is divided into two sections. In the first section, the improvements that can be done to the models created in this Thesis is discussed. This is done on a chapter by chapter basis. In the second section, we shall look at the potential ways in which this topic could be extended and future research areas that can be assessed.

7.1 Potential Improvements to the existing model

<u>Potential enhancements in vehicle emission statistics evaluation:</u>

Upstream emission factors of fossil fuels: In our model, as described in section 3.2, the upstream emissions of petrol and diesel for all the countries were taken from ecoinvent. The mapping of the diesel import export was excluded from the scope of the thesis owing to is complexity and enormity. We also decided to stick to the standard inventory to increase the reliability of our study. Nevertheless, we could improve this by creating processes of diesel and petrol production in each country (using a software like SimaPro), using standard inventory databases (such as ecoinvent) and the import export profile of crude and refined products. Nevertheless, validating the same would become a difficult task.

Fuel specifications could be included: In our thesis, the emissions of the diesel buses are calculated using the average speed model, viz. COPERT. COPERT further has the options of including the fuel specification which shall impact the emission inventory. Fuel specification might vary between countries. In our model, since the primary focus is laid on GHG emissions, fuel specifications would not affect the results. However, if this model is extended to investigate other emissions (such as heavy metals), it might be prudent to include the fuel specifications when and where available.

<u>Improvements to energy availability estimation:</u>

Residue availability factors: Some of the residues produced are already used for other purposes such as energy, ploughing back into soil, animal feed, etc. In our thesis, we introduced an availability factor to quantify the amount available for use in transport sector. These values were recovered from literature after careful considerations. This is also a technique commonly applied in this field of research. However, a more sophisticated approach could be developed to evaluate availability factors at district level. For instance, by knowing the type of crop, land, its slope, irrigation techniques, the amount of residue required to be ploughed back into the soil can be estimated. The quantity of residues required as animal feed is directly proportional to the animal population in that region. Thus, by collecting more data and information, a generalised method on residue availability could be developed.

Inclusion of MSW: In the types of bio-residues available for bio-energy purposes, we ignored MSW owing to its complexity and the lack of the ability to generate a generalised methodology. However, in future, when looking into specific countries/projects or cities, this can be included in the model. For smaller scope applications, this could be possible as the data might be available from the city/district corporation websites.

Location of process-based residues: In terms of transport distance of the biomass, process-based residues were treated the same as field-based residues. This is however not true. But for evaluating transport distances of process-based biomass residues, we need to know the location of all the mills and processing plants. Assuming that the mills/processing plants will be close to the location of the fields, it was presumed process-based residues operate the same way as field-based residues. In the future, this model can be improved by adding location of the processing plants if they are made available.

Possible upgrades in the estimation of bio-energy recovery emission:

Standardisation of the LCI: The life cycle inventory forms the crux of any LCA study. The system models which describe the linkage between activity datasets for forming a product system determines the inventory of the unit process as well. Hence, as far as possible, to maintain uniformity, the data for LCA were chosen from ecoinvent with "cut off" product system. However, as discussed before, since the scope of the work was broad, we had to choose datasets that were outside of ecoinvent as well. Since the primary focus was GHG and since emissions of manufacturing of vehicles and their end of life of treatment were left out of the scope of the work (primary focus was operation which dealt with energy flows), integration of these external data sources was possible. However, if in future, it is decided to include these and expand the scope of the work to beyond GHG emissions and include manufacturing and end of life in the scope, careful considerations need to be made to standardise the external data sources into the ecoinvent format (or even avoid them if possible).

Fuel dispersion/charging infrastructure models: Though from an energy/operational perspective, the emissions involved in development of the charging infrastructure or the disposal of fuel does not make a big contribution, they need to be included if the well to wheel analysis is expanded into a full LCA study.

Considering the emissions avoided due to prevention of open field burning and anaerobic decay: The system boundary established in our study starts from where the biomass residues are available. There could be an extended scenario which analyses "What happens if this biomass residues are not used for energy purposes?". Open field burning causes release of harmful pollutants in uncontrolled manner. The anaerobic decay of biomass releases methane which is a far more potent GHG than CO_2. Hence by using up these residues, a few ill environmental impacts could be avoided, which can be credited back to energy recovery. Such an extended boundary condition scenario can be explored in the future.

Biomass collection distance estimation: Presently, the biomass distribution has been done in a sub district level. The methodology of estimation of biomass transportation is established in section 5.1.2.2. Here, the import is done from neighbouring district. However, the biomass collection need not be restricted on district basis, but by radial collection. Hence in a future work, the district level boundaries can be replaced by a grid-based approach. Though the present method is accurate enough for the kind of evaluation we are doing, following a grid-based approach might increase the accuracy of the results further. Also, such an approach might require road network data at a resolution higher than what is available presently.

Potential enhancements to emission saving potential evaluation

Vehicle manufacturing emission can be included: The emissions of vehicle manufacturing has been ignored in the thesis. As this is a well to wheel analysis, that focuses on GHG emissions, the operational emissions are more relevant. However, when it comes to electric vehicles, the emissions of battery manufacturing and its second life could play a crucial role. Also, when we look at aspects outside of GHG emissions (such as human toxicity), the production and end of life could play a part. Hence, taking this forward, inclusion of the manufacturing and end of life emissions would add value to this work.

AC loads could be more specific: COPERT has the option to include the AC loads by including the climate conditions in the model. However, the same cannot be done for the electric vehicles as such databases do not exists. In tropical conditions of ASEAN, the air-condition loads could play a major part. Nevertheless, when considering the energy demands of electric vehicles in chapter 5, we made careful considerations to choose higher of the available values from literature to make sure the AC loads are accounted for. Still, building vehicle energy consumption models in the future might yield slightly more accurate results.

7.2 Possible extension of the topic

Cost assessment of the alternatives: This thesis is focussed on the emissions of the road transport alternatives. However, the cost of the alternatives could have a huge impact on their ability to be implemented. Hence it is important to estimate the cost of the alternatives to judge their viability.

Deeper analysis of hydrogen as an alternative fuel: An initial estimate of hydrogen, especially when derived from the existing sources of natural gas suggested that it might not be the most sustainable option. A brief estimate of deriving hydrogen from solar power was also done and compared to electric vehicles. However, this was done only from an energy consumption perspective and for cars. It also did not consider the operational perspective and the infrastructure needs. Hence before we make a strong conclusion that hydrogen might not be suitable entirely, a deeper study specific to ASEAN analysis is required. Other alternative sources of hydrogen, along with the cost, emissions and infrastructural needs can be analysed in addition to the work in this thesis.

Greater emphasis on other pollutants and their impacts (need special impact assessment methods): Through the thesis, it was made clear that emission of GHG would remain the prime focus. As discussed in chapter 2, this was done to make the line of argumentation more coherent and impactful. Also, the scope of the work (10 ASEAN counties) made the collection of life cycle inventory for such a big scale very difficult. However, when making informed decisions regarding the alternatives, other important impact categories such as human toxicity potential, eutrophication potential, etc. needs to be analysed as well. Nevertheless, for accomplishing this, one might have to reduce the scope of the work and look at smaller/more specific projects at a greater detail. Specific country/region/city/vehicle type could be taken as a subset of this thesis and a detailed LCA could be carried out on the same.

Making projections for the future: In this thesis, the emissions from road transport, bio-energy availability from biomass residues, emission saving potential of its use in transport sector is evaluated for present day. Hence the inferences made shall hold good for the present scenario. However, in the future, the situation could change. The electricity production mix of a country might change, the transport needs might grow, and the agricultural patterns might alter. Hence it would be interesting to have a look at the future projection scenarios of the analysis done in this thesis.

Establishing a continuous function for efficiency/emissions vs powerplant capacity: For the study on centralisation/decentralisation, an attempt was made to establish a relation between the powerplant size and the efficiency/emissions. The standard LCIs did not have much data on the same and hence data were taken from other literature sources. We were able to identify patterns but could not establish a clear continuous function. Hence distinct intervals were created. In a future work, a continuous function could be created by either investigating a larger database of powerplants or the physics of the conversion process involved in the powerplants. An optimisation of could be then run to identify the right size of the powerplant for a given biomass availability (instead of the discreet process followed here).

Trans border trade of ethanol and electricity: Since in many counties the bio-energy production can exceed the energy demand, a scenario that includes trans-border trade of bio-energy can be included. This is of interest for countries like Singapore and Brunei which do not have enough bio-resources of their own.

Appendix

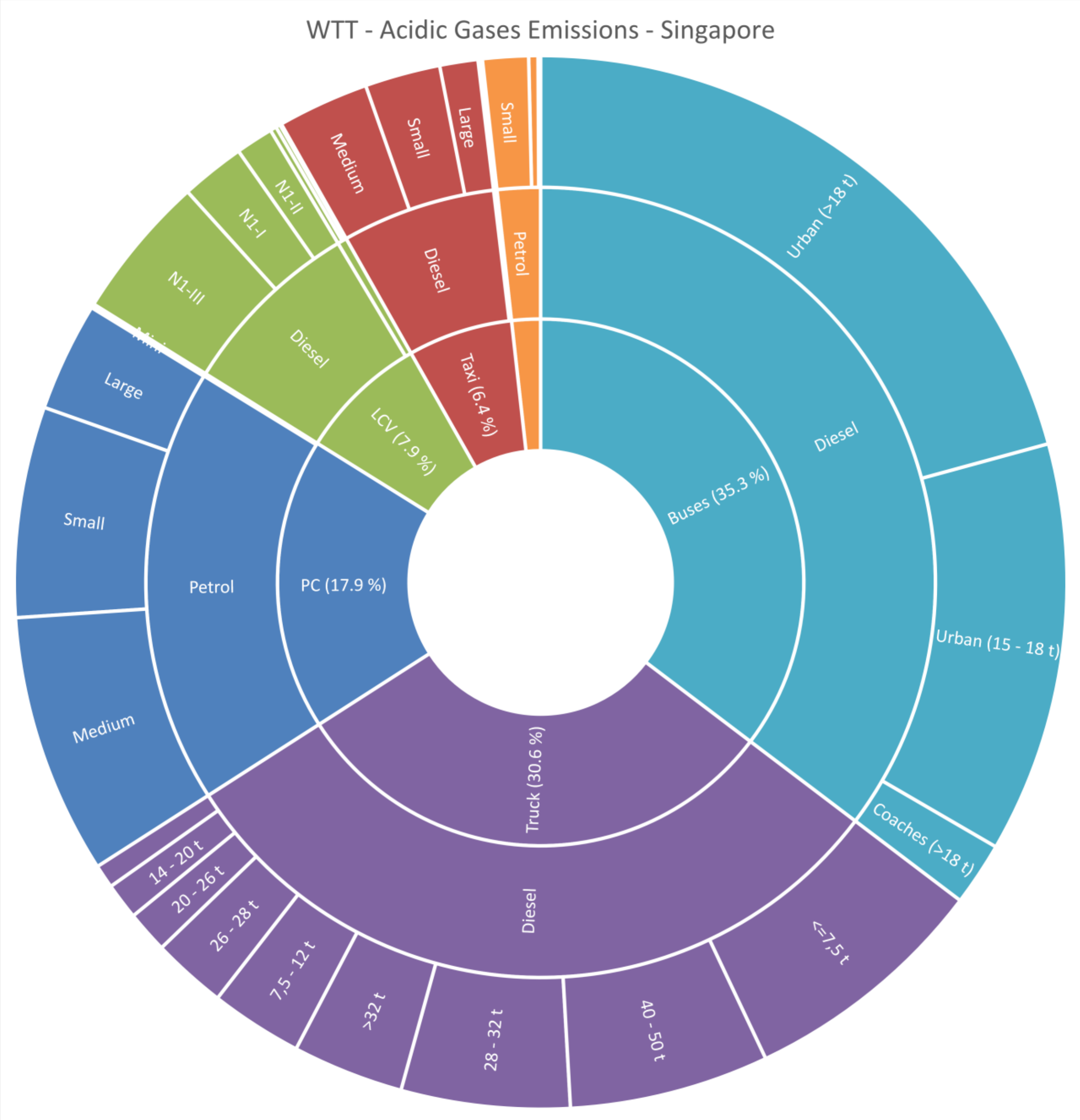

Figure A.1: Ratio of TTW acidic gases emissions of vehicles in Singapore classified by vehicle types, classes and fuel type

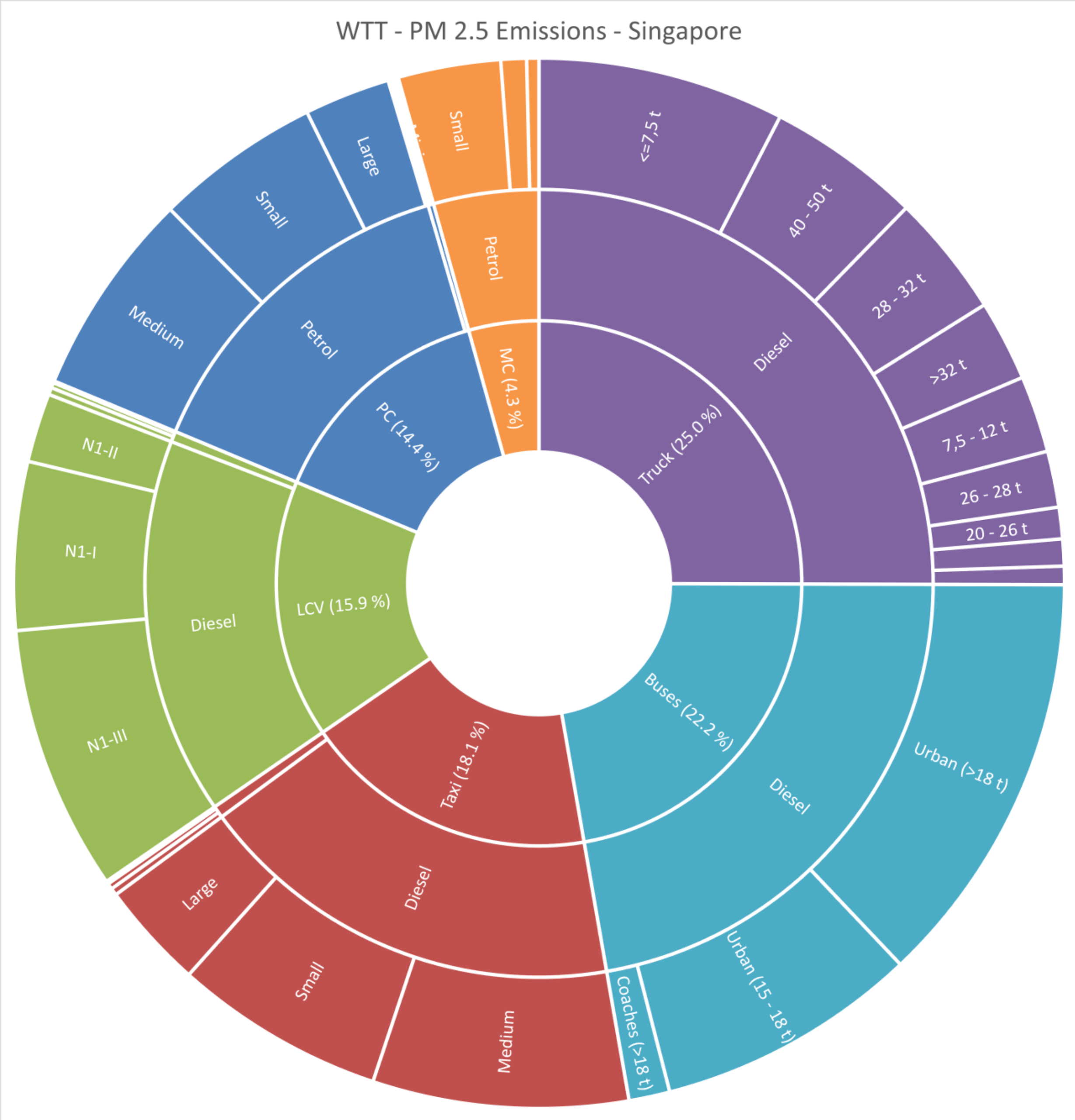

Figure A.2: Ratio of TTW PM 2.5 emissions of vehicles in Singapore classified by vehicle types, classes and fuel type

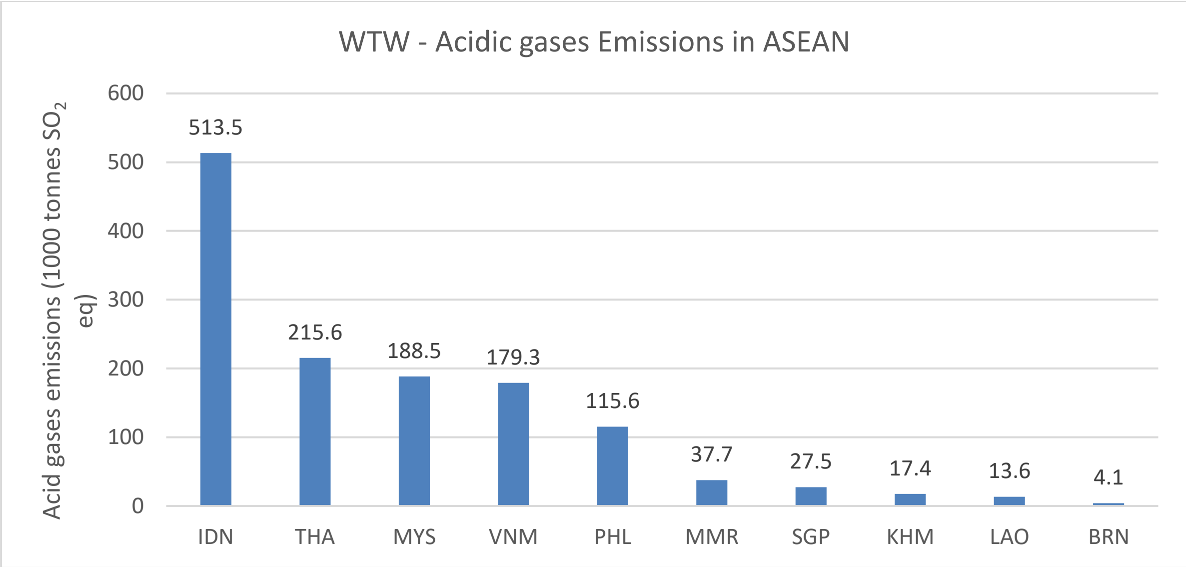

Figure A.3: WTW Acidic gases Emissions of ASEAN Nations

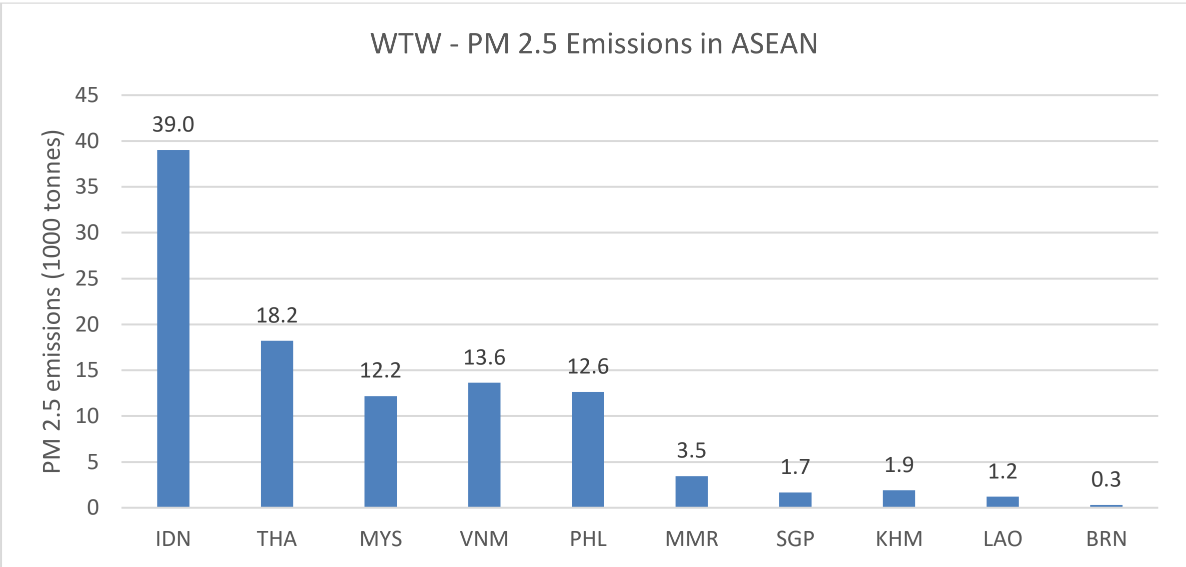

Figure A.4: WTW PM 2.5 Emissions of ASEAN Nations

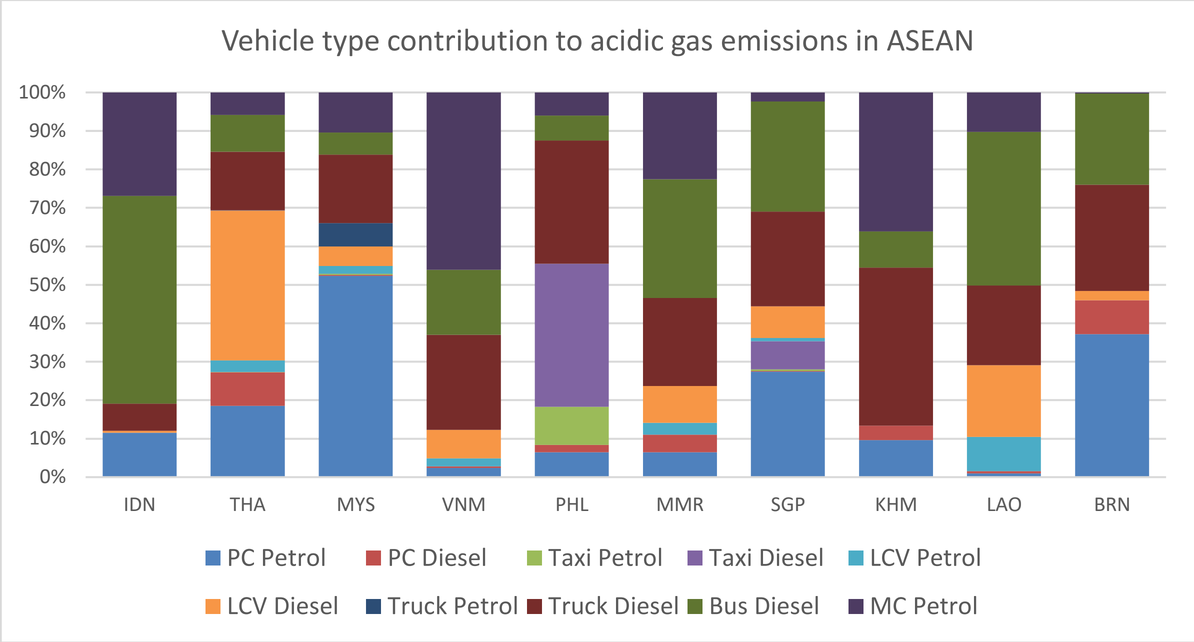

Figure A.5: Contribution of different vehicle types towards the WTW acidic gases emissions

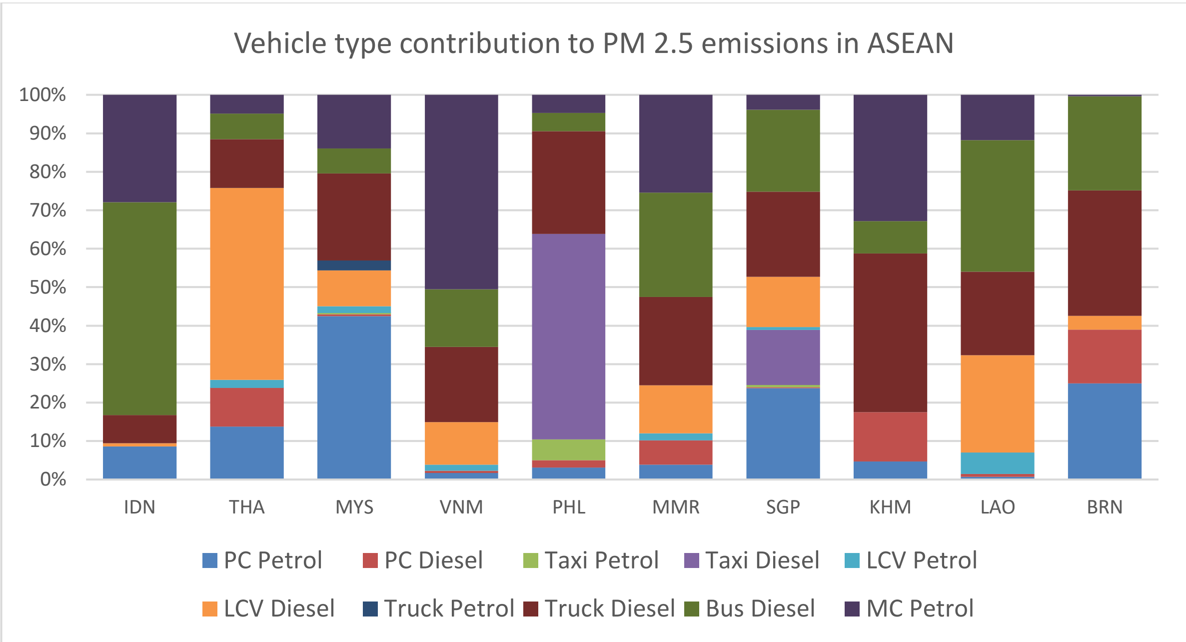

Figure A.6: Contribution of different vehicle types towards the WTW PM 2.5 emissions

Brunei vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	6460	0	0	0	**265608**
Small	69234	0	0	0	
Medium	100705	0	15123	0	
Large	39082	0	35004	0	
Total	215481	0	50127	0	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	**Euro 2**	**Euro 1**	**Euro 2**	
Small	3632	0			**4540**
Medium	908	0			
Large	0	0			
Total	4540	0			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	**Euro 2**	**Euro 1**	**Euro 2**	
LCV N1 <1305kg	0	0	0	0	**2579**
LCV N2 1306-1760	0	0	0	0	
LCV N3 1761-3500	0	0	2579	0	
Total	0	0	2579	0	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	**Euro 2**	**Euro 1**	**Euro 2**	
Petrol > 3,5 t	0	0	0	0	**10316**
Rigid <=7,5 t			6008	0	
Rigid 7,5 - 12 t			2669	0	
Rigid 12 - 14 t			267	0	
Rigid 14 - 20 t			223	0	
Rigid 20 - 26 t			189	0	
Rigid 26 - 28 t			239	0	
Rigid 28 - 32 t			426	0	
Rigid >32 t			295	0	
Articulated 40 - 50 t			0	0	
Total	0	0	10316	0	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	**Euro 2**	**Euro 1**	**Euro 2**	
Urban Midi <=15 t			0	0	**1999**
Urban Std. 15 - 18 t			1999	0	
Urban Art. >18 t			0	0	
Total			1999	0	

Table A.1: Vehicle population in Brunei classified by vehicle type, classes and fuel type

Cambodia vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	22356	0	8694	0	
Small	102470	0	39849	0	
Medium	137414	0	53439	0	372969
Large	6298	0	2449	0	
Total	268538	0	104431	0	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	1882331	0			
Medium	470583	0			2352914
Large	0	0			
Total	2352914	0			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	0	0	0	0	
LCV N2 1306-1760	0	0	0	0	0
LCV N3 1761-3500	0	0	0	0	
Total	0	0	0	0	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	0	0	0	0	
Rigid <=7,5 t			26572	0	
Rigid 7,5 - 12 t			11805	0	
Rigid 12 - 14 t			1183	0	
Rigid 14 - 20 t			987	0	
Rigid 20 - 26 t			837	0	45626
Rigid 26 - 28 t			1056	0	
Rigid 28 - 32 t			1883	0	
Rigid >32 t			1303	0	
Articulated 40 - 50 t			0	0	
Total	0	0	45626	0	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			0	0	
Urban Std. 15 - 18 t			4928	0	4928
Urban Art. >18 t			0	0	
Total			4928	0	

Table A.2: Vehicle population in Cambodia classified by vehicle type, classes and fuel type

Indonesia vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	2692227	1858298	0	0	12599038
Small	2692227	1858298	0	0	
Medium	680190	469498	0	0	
Large	1389324	958975	0	0	
Total	7453968	5145069	0	0	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	22928324	51452668			92976240
Medium	4299061	9647375			
Large	1433020	3215792			
Total	28660405	64315835			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	0	0	78628	42437	327204
LCV N2 1306-1760	0	0	27626	14910	
LCV N3 1761-3500	0	0	106255	57348	
Total	0	0	212509	114695	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	0	0	0	0	5907932
Rigid <=7,5 t			2789395	1505495	
Rigid 7,5 - 12 t			679885	366948	
Rigid 12 - 14 t			29955	16167	
Rigid 14 - 20 t			89866	48502	
Rigid 20 - 26 t			78711	42482	
Rigid 26 - 28 t			56401	30441	
Rigid 28 - 32 t			56401	30441	
Rigid >32 t			56401	30441	
Articulated 40 - 50 t			0	0	
Total	0	0	3837015	2070917	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			1649132	21783	2398846
Urban Std. 15 - 18 t			239480	3163	
Urban Art. >18 t			478961	6327	
Total			2367573	31273	

Table A.3: Vehicle population in Indonesia classified by vehicle type, classes and fuel type

Laos vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	5445	9940	0	0	73799
Small	7260	13254	0	0	
Medium	5445	9940	0	0	
Large	0	0	22515	0	
Total	18150	33134	22515	0	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	974703	0			1218379
Medium	243676	0			
Large	0	0			
Total	1218379	0			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	8767	12155	47558	0	185109
LCV N2 1306-1760	3080	4271	16710	0	
LCV N3 1761-3500	11874	16426	64268	0	
Total	23721	32852	128536	0	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	0	0	0	0	44293
Rigid <=7,5 t			25796	0	
Rigid 7,5 - 12 t			11461	0	
Rigid 12 - 14 t			1148	0	
Rigid 14 - 20 t			958	0	
Rigid 20 - 26 t			812	0	
Rigid 26 - 28 t			1025	0	
Rigid 28 - 32 t			1828	0	
Rigid >32 t			1265	0	
Articulated 40 - 50 t			0	0	
Total	0	0	44293	0	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			52136	0	56256
Urban Std. 15 - 18 t			4120	0	
Urban Art. >18 t			0	0	
Total			56256	0	

Table A.4: Vehicle population in Laos classified by vehicle type, classes and fuel type

Malaysia vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	443637	222611	2140	1074	
Small	2033472	1020369	9810	4922	
Medium	2726928	1368335	13155	6601	8041646
Large	124975	62711	603	303	
Total	5329012	2674026	25708	12900	
Taxi	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	95	78	1	1	
Small	4205	3842	34	28	
Medium	25875	15892	188	121	59394
Large	4902	4059	40	33	
Total	35077	23871	263	183	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	5892732	2246408			
Medium	76685	29234			8351598
Large	77134	29405			
Total	6046551	2305047			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	46704	13057	130826	36574	
LCV N2 1306-1760	16410	4587	45966	12850	613946
LCV N3 1761-3500	63113	17644	176791	49424	
Total	126227	35288	353583	98848	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	53391	0	0	0	
Rigid <=7,5 t			68070	19030	
Rigid 7,5 - 12 t			38146	10664	
Rigid 12 - 14 t			3812	1066	
Rigid 14 - 20 t			3166	885	
Rigid 20 - 26 t			2677	749	219021
Rigid 26 - 28 t			3378	944	
Rigid 28 - 32 t			6025	1684	
Rigid >32 t			4169	1165	
Articulated 40 - 50 t			0	0	
Total	53391	0	129443	36187	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			158	37	
Urban Std. 15 - 18 t			2764	643	41573
Urban Art. >18 t			30803	7168	
Total			33725	7848	

Table A.5: Vehicle population in Malaysia classified by vehicle type, classes and fuel type

Myanmar vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	48612	0	34628	0	416202
Small	97225	0	69256	0	
Medium	72919	0	51942	0	
Large	24306	0	17314	0	
Total	243062	0	173140	0	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	3421357	0			4276696
Medium	855339	0			
Large	0	0			
Total	4276696	0			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	11844	0	39876	0	139783
LCV N2 1306-1760	4161	0	14010	0	
LCV N3 1761-3500	16006	0	53886	0	
Total	32011	0	107772	0	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	2481	0	0	0	53776
Rigid <=7,5 t			29873	0	
Rigid 7,5 - 12 t			13272	0	
Rigid 12 - 14 t			1330	0	
Rigid 14 - 20 t			1110	0	
Rigid 20 - 26 t			941	0	
Rigid 26 - 28 t			1187	0	
Rigid 28 - 32 t			2117	0	
Rigid >32 t			1465	0	
Articulated 40 - 50 t			0	0	
Total	2481	0	51295	0	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			0	0	26746
Urban Std. 15 - 18 t			26746	0	
Urban Art. >18 t			0	0	
Total			26746	0	

Table A.6: Vehicle population in Myanmar classified by vehicle type, classes and fuel type

Philippine's vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	121858	17585	23211	3350	
Small	162477	23447	30948	4466	
Medium	121858	17585	23211	3350	1283961
Large	350833	171257	111951	96574	
Total	757026	229874	189321	107740	
MC	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	2157737	2338478			
Medium	0	0			4496215
Large	0	0			
Total	2157737	2338478			
LCV	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	0	0	0	0	
LCV N2 1306-1760	0	0	0	0	0
LCV N3 1761-3500	0	0	0	0	
Total	0	0	0	0	
Truck	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	0	0	0	0	
Rigid <=7,5 t			232135	5561	
Rigid 7,5 - 12 t			103134	2471	
Rigid 12 - 14 t			10333	248	
Rigid 14 - 20 t			8622	207	
Rigid 20 - 26 t			7310	175	408139
Rigid 26 - 28 t			9223	221	
Rigid 28 - 32 t			16451	394	
Rigid >32 t			11381	273	
Articulated 40 - 50 t			0	0	
Total	0	0	398589	9550	
Buses	**Petrol**		**Diesel**		**Total**
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			0	0	
Urban Std. 15 - 18 t			30977	373	31350
Urban Art. >18 t			0	0	
Total			30977	373	

Table A.7: Vehicle population in Philippines classified by vehicle type, classes and fuel type

Thailand vehicle database

PC	Petrol				Diesel				Total
	Euro 1	Euro 2	Euro 3	Euro 4	Euro 1	Euro 2	Euro 4	Euro 5	
Mini	65826	62679	102437	112572	27686	26362	43084	47346	
Small	312675	297724	486578	534719	131507	125219	204648	224896	
Medium	419643	399577	653039	717649	176497	168057	274660	301834	6099911
Large	24685	23505	38414	42215	10382	9886	16156	17755	
Total	822830	783484	1280468	1407154	346072	329523	538549	591831	
Taxi	Petrol				Diesel				Total
	Euro 1	Euro 2	Euro 3	Euro 4	Euro 1	Euro 2	Euro 4	Euro 5	
Mini	4	30	65	31	1	12	25	12	
Medium	88	702	1495	712	35	277	589	281	7144
Large	59	468	997	474	23	185	393	187	
Total	150	1200	2556	1217	59	473	1008	480	
MC	Petrol				Diesel				Total
	Euro 1	Euro 2	Euro 3	Euro 4	Euro 1	Euro 2	Euro 4	Euro 5	
Small	1152762	3521586	6938122	4500501					
Medium	216143	660297	1300898	843844					20141214
Large	72048	220099	433633	281281					
Total	1440953	4401982	8672653	5625626					
LCV	Petrol				Diesel				Total
	Euro 1	Euro 2	Euro 3	Euro 4	Euro 1	Euro 2	Euro 4	Euro 5	
LCV N1 <1305kg	54705	50414	25673	24522	661206	694781	353809	337954	
LCV N2 1306-1760	19221	17713	9020	8616	232316	244112	124311	118741	5954227
LCV N3 1761-3500	73925	68127	34693	33138	893522	938893	478120	456695	
Total	147851	136254	69386	66276	1787044	1877786	956240	913390	
Truck	Petrol				Diesel				Total
	Euro 1	Euro 2	Euro 3	Euro 4	Euro 1	Euro 2	Euro 4	Euro 5	
Petrol > 3,5 t	471	349	146	191	0	0	0	0	
Rigid <=7,5 t					159505	118163	49421	64755	
Rigid 7,5 - 12 t					158955	117756	49251	64531	
Rigid 12 - 14 t					13898	10296	4306	5642	
Rigid 14 - 20 t					2352	1742	729	955	
Rigid 20 - 26 t					941	697	291	382	829190
Rigid 26 - 28 t					470	348	146	191	
Rigid 28 - 32 t					470	348	146	191	
Rigid >32 t					470	348	146	191	
Art. 40 - 50 t					0	0	0	0	
Total	471	349	146	191	337061	249698	104436	136838	
Buses	Petrol				Diesel				Total
	Euro 1	Euro 2	Euro 3	Euro 4	Euro 1	Euro 2	Euro 4	Euro 5	
Urban Midi <=15 t					2018	1376	1022	859	
Urb Std. 15 - 18 t					18160	12386	9198	7734	105507
Coach Art. >18 t					20178	13762	10220	8594	
Total					40356	27524	20440	17187	

Table A.8: Vehicle population in Thailand classified by vehicle type, classes and fuel type

Vietnam vehicle database

PC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Mini	10637	28361	925	6622	
Small	20092	53571	1747	12508	
Medium	53777	143382	4676	33477	**840397**
Large	107553	286763	9352	66954	
Total	192059	512077	16700	119561	

MC	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Small	16086644	22987856			
Medium	0	0			**39074500**
Large	0	0			
Total	16086644	22987856			

LCV	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
LCV N1 <1305kg	15541	34443	62165	137770	
LCV N2 1306-1760	5419	12009	21674	48035	**439922**
LCV N3 1761-3500	6397	14176	25587	56706	
Total	27357	60628	109426	242511	

Truck	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Petrol > 3,5 t	0	0	0	0	
Rigid <=7,5 t			41283	91491	
Rigid 7,5 - 12 t			0	0	
Rigid 12 - 14 t			46416	102869	
Rigid 14 - 20 t			0	0	
Rigid 20 - 26 t			0	0	**285844**
Rigid 26 - 28 t			1177	2608	
Rigid 28 - 32 t			0	0	
Rigid >32 t			0	0	
Articulated 40 - 50 t			0	0	
Total	0	0	88876	196968	

Buses	Petrol		Diesel		Total
	Euro 1	Euro 2	Euro 1	Euro 2	
Urban Midi <=15 t			45980	12599	
Urban Std. 15 - 18 t			24772	6788	**101964**
Urban Art. >18 t			9282	2543	
Total			80034	21930	

Table A.9: Vehicle population in Vietnam classified by vehicle type, classes and fuel type

	Available Energy *(GWh)*										
Biomass Residue type	**BRN**	**KHM**	**IDN**	**LAO**	**MYS**	**MMR**	**PHL**	**SGP**	**THA**	**VNM**	**Total**
Rice Straw	3.6	18258.3	138599.4	6640.3	5107.8	55935.8	35854.4	0.0	70121.7	85632.0	416153.4
Rice Husk	0.8	4244.3	32218.3	1543.6	1187.3	13002.6	8334.6	0.0	16300.3	19905.7	96737.6
Maize Stalk	0.1	1215.1	24266.0	1507.5	115.1	2228.4	9670.1	0.0	6636.5	6804.4	52443.1
Maize Cob	0.0	717.3	14323.7	889.8	67.9	1315.4	5708.1	0.0	3917.4	4016.5	30956.1
Maize Husk	0.0	301.3	6017.3	373.8	28.5	552.6	2397.9	0.0	1645.7	1687.3	13004.4
Sugarcane Bagasse	0.0	55.5	3114.9	109.1	19.8	892.0	2946.2	0.0	9252.0	1860.7	18250.1
Sugarcane Leave & Top	0.0	338.5	19010.6	665.7	120.7	5443.7	17980.5	0.0	56465.4	11356.2	111381.2
Oil Palm Shell	0.0	0.0	1438.3	0.0	1147.4	0.0	5.7	0.0	153.6	0.0	2744.9
Oil Palm EFB	0.0	0.0	26718.0	0.0	21314.0	0.0	105.4	0.0	2852.6	0.0	50990.0
Oil Palm Fibre	0.0	0.0	6594.1	0.0	5260.4	0.0	26.0	0.0	704.0	0.0	12584.6
Oil Palm POME	0.0	0.0	8908.4	0.0	7106.5	0.0	35.1	0.0	951.1	0.0	17001.2
Oil Palm Frond	0.0	0.0	7341.7	0.0	5856.8	0.0	29.0	0.0	783.8	0.0	14011.3
Cassava Stalk	0.5	1352.3	4046.1	189.3	13.8	106.5	399.0	0.0	5109.5	1649.4	12866.3
Coconut Husk	0.0	51.0	16106.0	0.0	569.4	374.0	13512.5	0.1	888.9	1147.5	32649.5
Coconut Shell	0.0	16.1	5066.6	0.0	179.1	117.7	4250.7	0.0	279.6	361.0	10270.9
Coconut Frond	0.0	42.7	13463.0	0.0	475.9	312.7	11295.1	0.1	743.0	959.2	27291.8
Coffee Husk	0.0	1.0	1665.6	212.1	39.6	19.7	186.8	0.0	119.2	3481.8	5725.6
Groundnut Shell/Husk	0.0	30.2	1350.2	48.4	0.7	1385.4	29.3	0.0	47.4	495.7	3387.2
Groundnut Straw	0.0	111.2	4966.6	177.9	2.4	5096.4	107.8	0.0	174.2	1823.6	12460.1
Logging residues	104.7	137.8	61074.8	834.4	17372.5	4955.8	3765.1	0.0	14248.5	6596.1	109089.7
Cattle Manure	0.0	49.2	281.9	28.9	13.4	249.6	42.4	0.0	87.4	87.5	840.4
Buffalo Manure	0.2	48.6	106.8	84.9	8.6	233.9	209.6	0.0	87.7	184.2	964.6
Pig Manure	0.2	324.4	1244.4	344.1	260.3	1589.0	1787.2	41.0	1184.6	3963.0	10738.3
Poultry Manure	160.1	177.3	15352.6	278.5	2589.4	1716.0	1444.7	35.4	2389.5	2620.2	26763.6
Goat Manure	0.0	0.0	62.4	1.5	1.7	13.2	12.4	0.0	1.5	4.6	97.4
Sheep Manure	0.0	0.0	44.7	0.0	0.4	2.6	0.1	0.0	0.2	0.0	48.0

Table A.10: Energy available from the different biomass residues in the ASEAN countries

	Coal split (kt)				Oil split (kt)	
	Anthracite	Other bituminous coal	Sub bituminous coal	Lignite	Diesel	HFO
BRN	0	0	0	0	11	0
KHM	0	0	490	0	21	65
IDN	0	0	65975	0	5354	1036
MYS	0	21649	0	0	638	271
MMR	0	113	0	0	16	0
PHL	0	13276	2311	0	332	1064
SGP	0	372	0	0	2	64
THA	0	8500	0	17020	36	363
VNM	14084	1096	0	0	55	119

Table A.11: Split of kind of coal and oil for electricity production

Powerplant type	ecoinvent Activity name	GWP *(g CO_2 eq/kWh)*	AP *(g SO_2 eq/kWh)*	PM 2.5 *(g/kWh)*
Hard Coal	Electricity, high voltage {RoW}| electricity production, hard coal | Cut-off, U	1058.4	9.24	0.387
Lignite	Electricity, high voltage {RoW}| electricity production, lignite | Cut-off, U	1294.6	8.29	8.836
Natural Gas – GT	Electricity, high voltage {RoW}| electricity production, natural gas, conventional power plant | Cut-off, U	600.5	0.33	0.022
Natural Gas – CCGT	Electricity, high voltage {RoW}| electricity production, natural gas, combined cycle power plant | Cut-off, U	430.4	0.18	0.015
HFO - Oil	Electricity, high voltage {RoW}| electricity production, oil | Cut-off, U	916.8	7.60	0.131
Diesel	Electricity, high voltage {RoW}| heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction	718.8	1.95	0.068
Biomass/ Waste	Electricity, high voltage {RoW}| heat and power co-generation, wood chips, 6667 kW | Cut-off, U	62.7	1.56	0.438
Hydropower	Electricity, high voltage {RoW}| electricity production, hydro, reservoir, tropical region | Cut-off, U	72.7	0.02	0.006
Geothermal	Electricity, high voltage {RoW}| electricity production, deep geothermal | Cut-off, U	81.2	0.36	0.082
Solar PV	Electricity, low voltage {RoW}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U	85.8	0.47	0.079
Wind	Electricity, high voltage {RoW}| electricity production, wind, <1MW turbine, onshore | Cut-off, U	16.1	0.09	0.019

Table A.12: Power plant emission inventory

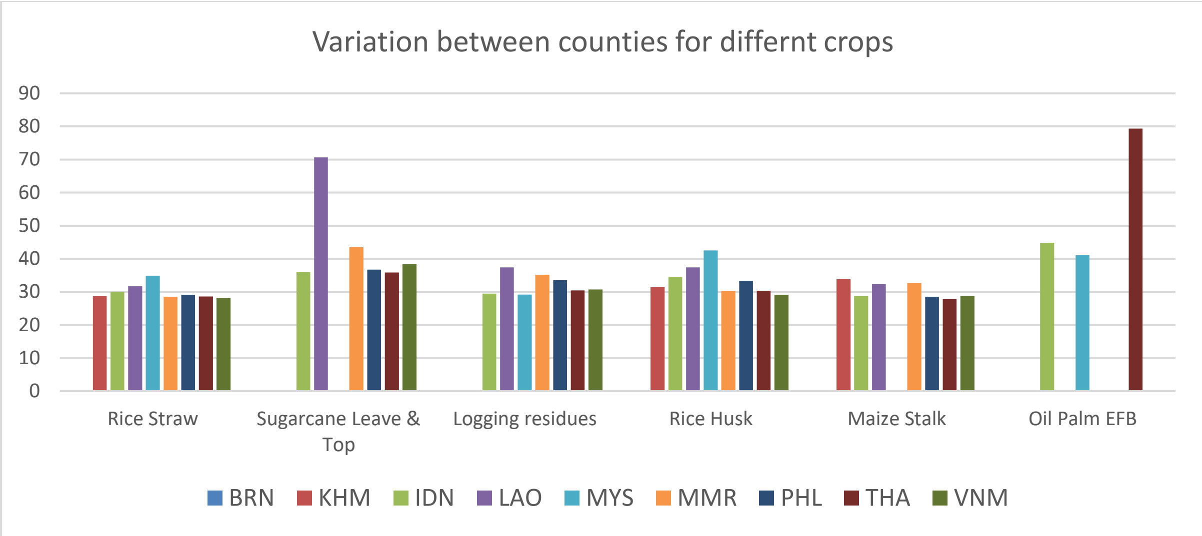

Figure A.7: Specific GHG emissions of energy recovery from various residues for all the countries, for 1MW combustion powerplant with briquetting configuration

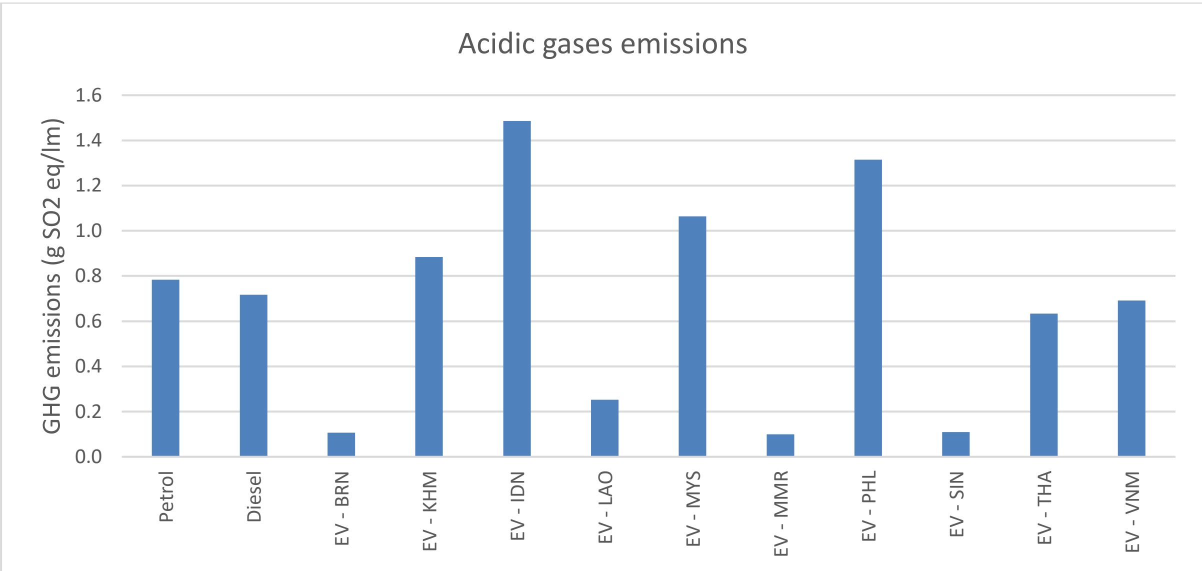

Figure A.8: Acidic gases emissions of a mid-size passenger car using grid electricity for different ASEAN countries

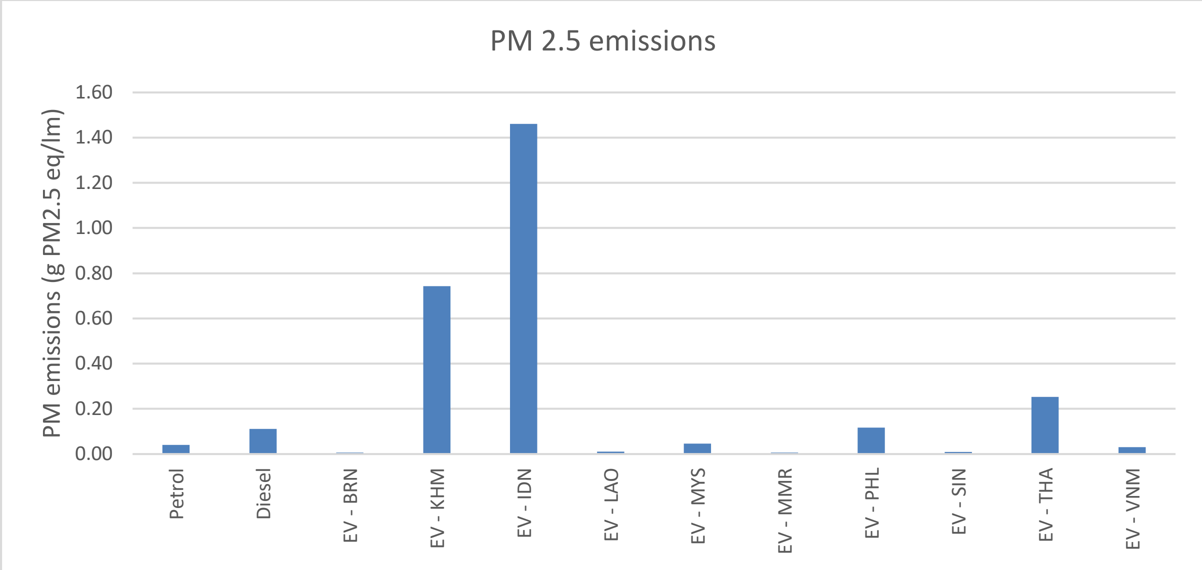

Figure A.9: PM 2.5 emissions of a mid-size passenger car using grid electricity for different ASEAN countries

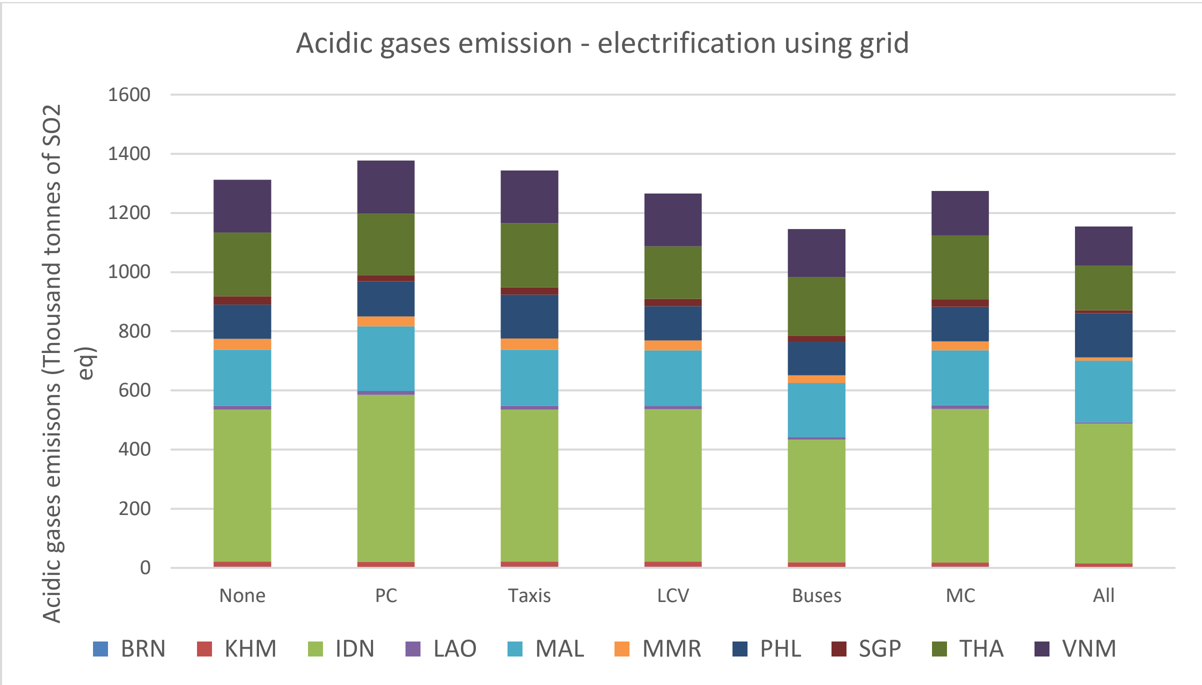

Figure A.10: WTW Acidic gases emissions of transport electrification in ASEAN using Grid Electricity

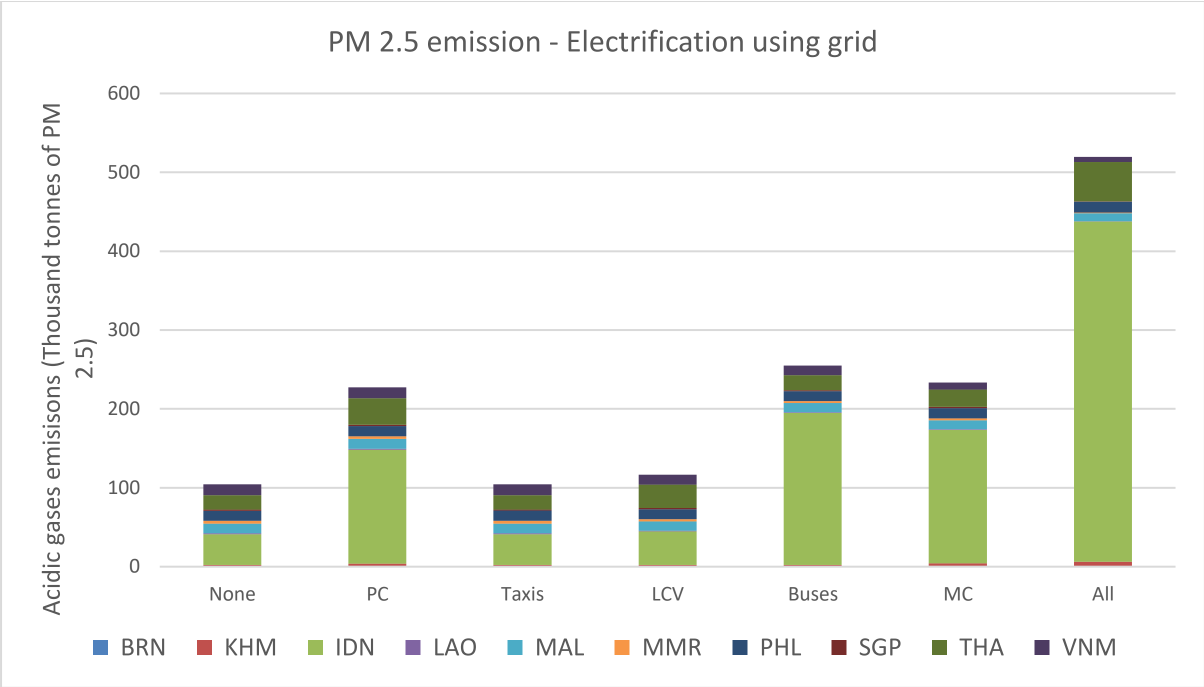

Figure A.11: WTW PM 2.5 emissions of transport electrification in ASEAN using Grid Electricity

Abbreviations

AF – Availability factor
AP – Acidification potential
ASEAN – Association of Southeast Asian Nations
BCO – Bio-ethanol from corn
BEV – Battery electric vehicle
BRN – Brunei
BSB – Bio-ethanol from sugar beet
BSC- Bio-ethanol from sugarcane
BTW – Biomass transportation work
BWS – Bio-ethanol from wheat straw
BWW – Bio-ethanol from wood waste
CAA – Clean Air Asia
CCGT – Combined cycle gas turbine
CDM – Clean development mechanism
CNG – Compressed natural gas
CPO – Crude palm oil
DEFC – Direct ethanol fuel cell
EAU – Austria electricity mix
EFB – Empty Fruit Bunches
EFR – France electricity mix
EGE – Germany electricity mix
ESW – Sweden electricity mix
EUCAR – The European Council for Automotive research and development
FAOSTAT – Food and Agricultural Organisation Corporation Statistical Database
FC – Fuel cell
FCEV – Fuel cell electric vehicles
FFB – Fresh Fruit Bunches
GDP – Gross domestic product
GEF – Grid emission factor
GHG – Greenhouse gas
GREET – The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GT – Gas turbine
HEV – Hybrid electric vehicle
HNC – Hydrogen from central reforming of natural gas
HNO – Hydrogen from on-site reforming of natural gas
HV – High voltage
ICE – Internal combustion engine
IDN – Indonesia
IEA – International Energy Agency
IGES – Institute for Global Environmental Strategies
IPCC – Intergovernmental Panel on Climate Change

IRENA – International Renewable Energy Agency
JRC – Joint Research Centre
KHM – Cambodia
LAO- Laos
LCA – Life cycle assessment
LCI – Life cycle inventory
LCIA – Life cycle impact assessment
LCV – Light commercial vehicle
LHV – Lower heating value
LTA – Land transport authority
LV – Low voltage
MC – Motorcycle
MMR – Myanmar
MSW – Municipal solid waste
MYS – Malaysia
NEDC – New European drive cycle
NF – Normalisation factor
NG – Natural gas
NGP – Natural gas distributed through pipeline
OS – On site
PC – Passenger car
PEM – Polymer electrolyte membrane
PHL – Philippines
PM - Particulate matter
POME – Palm oil mill effluent
RH – Relative humidity
RoW – Rest of world
RPR – Residue production ratio
SGP – Singapore
THA – Thailand
TTW – Tank to wheel
UN – United nations
VKT – Vehicle kilometres travelled
VNM – Vietnam
VS – Volatile solids
WTT – Well to tank
WTW – Well to wheel

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