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A Techno-Economical and Automotive Emissions Impact Study of Global Biodiesel Usage in Diesel Engines

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Abstract – *In recent years, biodiesel has arrived at the forefront, as a mainstream alternative energy, due to its advantages properties such as renewability, compatibility with existing automotive infrastructures and diesel engines, cleaner emissions. Many studies have been conducted to improve the maturity of biodiesel production technology, and fuel application. However, the global-scale economical and emissions impacts of first generation biodiesel is still not being adequately addressed. This requires immediate attention as the current economical setback for biodiesel is affected by low crude oil price. In this study, the correlations between the biodiesel production feasibility, crude oil price, and feedstock availability are defined. By using a data-driven predictive model, insights can be drawn for the worldwide profitability, potential level of diesel replacement using biodiesel, and environmental impact. The model allows prediction to be done on potential biodiesel production at a country-region level, at different crude oil prices and fuel blending ratios. It was also predicted that up to 9% of total global diesel consumption could be replaced by profitable biodiesel, if crude oil price rises up to USD 135 per barrel and factoring in refinery cost of USD 0.05 per litre. Countries near the equatorial belt with abundance palm oil feedstock such as Malaysia, Papua New Guinea and Indonesia could potentially augment their gross domestic products by 10.36%, 7.67% and 5.57%, respectively. If all non-domestic usage feedstock is converted into biodiesel for automotive usage, there will be conclusive reduction of engine-out emissions such as unburnt hydrocarbons and particulate matter. Ultimately, this model proves that there is high potential for mass adoption of biodiesel to supplant fossil diesel globally, allowing the generation of income, improving energy security and produces cleaner automotive emissions.*

Keywords: Biodiesel, crude oil price, emissions, refinery cost

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1.0 INTRODUCTION

Majority of the energy consumption today, are still being satisfied by non-renewable energy such as fossil petroleum, coal, natural gas, and shale oil. The rapid growth in worldwide energy consumption has driven the development of sustainable energy sources, owing to the dwindling of fossil fuel supplies (Ng et al., 2010). In recent decades, biodiesel has proved to be a viable alternative fuel, due to its capability to be renewable, and compatibility to existing compression ignition engine, with advantages such as reduced emissions level, biodegradability, and environmentally friendly. Biodiesel's desirable properties, can also be extended for blending in fossil diesel, to reduce the dependency on non-renewable fuel, while also contributing to cleaner emissions.

In the United States of America alone, biodiesel consumption and production has seen an increased from 680 and 590 thousand barrels, respectively, to 4800 and 3400 thousand barrels, a significant increase of 6 times over a decade (International Energy Agency, 2016). The production in the country is insufficient to satisfy the required level of consumption, thus biodiesel is imported from other countries. Biodiesel fuel can support the high consumption demand due to its high versatility in biodiesel feedstocks, as currently there exist more than 15 types of feedstock, supported by oil crops and animal lipids (Issariyakul & Dalai, 2014). However, four types of oil crop are contributing to majority of biodiesel production globally, namely, soybean, palm, coconut, and rapeseed oil.

The aforementioned feedstocks are classified as first generation feedstocks, which function primarily as food crop. Currently, biodiesel economics has been heavily dictated by the price of crude oil, and the competition between food usages of the crops, which determines cost of the feedstocks. It has been found that, 70-95% of the total production cost of biodiesel, are mainly accounted by the feedstock price (Bhuiya et al., 2016). Biodiesel is unable to be produced profitably, due to the crude oil price setting a new low in the past two years, resulting the continuing need for government incentives and subsidies to support biodiesel production industry.

Most biodiesel researches are done on technical investigation of the production and combustion of the biodiesel fuel (Basha et al., 2009; Ng et al., 2012a). While economic and social implication of biodiesel production has also been studied (Demirbas, 2009). Despite the large research input in first generation feedstocks, there is a gap in knowledge understanding the economical standings of first generation feedstocks, particularly in the feasibility of the worldwide implementation of biodiesel. In order to fully realise the potential of biodiesel, in depth analysis of the crude oil price and feedstock availability for biodiesel has to be conducted.

In this study, a data-driven predictive model is used to comprehensively gauge the feasibility of using biodiesel to replace fossil diesel in a free-market condition. This allows the potential global availability of biodiesel feedstock for each country and feedstock to be quantified. The model would also be sensitive towards crude oil price and refinery cost, ensuring that only profitable biodiesel is predicted. It is envisioned that this study will provide quantitative prediction of the economical feasibility of biodiesel and also the engine-out emissions impacts from the automotive industry if biodiesel supplants fossil diesel.

2.0 METHODOLOGY

A data-driven predictive model was developed to analyse the economical feasibility of biodiesel globally, while also forecasting the emissions impacts if the biodiesel were used in the automotive industry. The model is modified from a previous economical feasibility model (Wu et al., 2015), with additions to include crude oil price and refinery cost as independent factors. Primary sources of data were obtained from the Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT, 2016), Index Mundi (Index Mundi, 2016) and US Energy Information Administration.

For the model developed, a business-as-usual totally free market scenario is assumed, and all forms of government interventions such as subsidies or protectionism acts were not considered.

2.1 Lipid Export Value

Exported quantity of lipids such as vegetable oils and animal fats from all countries were obtained from the Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT). In this model, only exported quantity was analysed so that domestic demand for the lipids are not affected. Minor lipids below the minimum threshold value of 50,000 tonnes were filtered off, as they would not be feasible candidates for commercial production or to exploit economies of scale. Four recurring factors, refinery cost, feedstock type, country, crude oil price are given the subscript of *g*, *i*, *j*, *k*, respectively.

The upper boundary lipid export value per unit volume, $ULEV_{gk}$, is the highest cost on the feedstock, over which losses will be made. This is mainly tied to the diesel price per unit volume, DP_k, and refinery cost per unit volume, RC_g, as they are the two largest factors in determining the greatest possible cost for biodiesel to replace the existing usage of diesel. $ULEV_{gk}$ is represented by:

$$ULEV_{gk} = \frac{DP_k}{RBL} - RC_g \tag{1}$$

where *RBL* is the conversion ratio from biodiesel to lipid. As biodiesel production has matured over decades of optimisation with yield reaching 99%, *RBL* is fixed at 0.99. RC_g includes the cost of methanol, operation costs and the potential expenditure or profit from the co-product glycerol.

DP_k is the variable used in the model to mimic the price of crude oil, k, which is presume to correlate linearly and have a range from 20 to 200 USD/bbl. DP_k is represented by:

$$DP_k = k \times RDC \tag{2}$$

where *RDC* denotes the ratio of diesel price to crude oil price per unit volume, and is set at a value of 1.24, based on a 10-year average value.

2.2 Biodiesel Volume

The maximum biodiesel volume that can be potentially be produced without incurring losses on a country level, can be calculated from the profitable potential biodiesel volume, $PPBV_{gjk}$:

$$PPBV_{gjk} = \left(\sum_{i=1} \frac{(EO \cup EF)_{gjk}}{LD}_{i}\right) \times RR \times RBL \quad (3)$$

where EO_{gjk} and EF_{gjk} are the exported vegetable oil and exported animal fat, respectively. They are filtered by $ULEV_{gk}$, where selection is only made when the price is lower than that of $ULEV_{gk}$. LD_i is the lipid density for each respective feedstock. *RR* is the refining ratio, and the value is taken to be 0.98 to account for losses.

2.3 Fuel Blend Ratio

The plausible fuel blend ratio, PFB_{gjk}, is the highest possible fuel blend achievable for each country, and is shown by:

$$PFB_{gjk} = \frac{PPBV_{gjk} \cup BP_j}{DV_j} \quad (4)$$

where BP_j is the current biodiesel production volume, while DV_j is the current diesel consumption volume. Here, $PPBV_{gjk}$ and BP_j are summed to obtain the greatest possible volume of biodiesel achievable. The value is then divided by DV_j to ascertain the maximum fuel blend ratio.

2.4 Emissions

For the impacts of biodiesel usage on emissions, the model factors in the scenario if the biodiesel is used for automotive purposes. Here, empirical equations with regards to automotive diesel engine emissions from Ng et al. (2012b) were used to predict the change in emissions such as carbon monoxide (CO), nitrogen oxide (NO), unburnt hydrocarbon (UHC) and particulate matter (PM).

Percentage change for each emission for each fuel blend ratio as compared to diesel fuel (on a global scale), E_{fh}, is represented by:

$$E_{fh} = \left[\left(\sum_{i=1} PCE_{hi} \times F_{fi}\right) + PCEB \times BPF_f\right] \times FB_f \quad (5)$$

where PCE_{hi} is the percentage change of each emission for each feedstock, F_i denotes the fraction of feedstock that can be used to produce biodiesel, *PCEB* is the percentage change of each emission for current biodiesel production, BPF_f represents the fraction of current biodiesel production, and FB_f is the fuel blend levels.

3.0 RESULTS AND DISCUSSION

3.1 Relationship of Global Fuel Blend Levels with Crude Oil Price and Refinery Cost

The relationship of the global biodiesel level in blends with diesel fuel against that of crude oil price and refinery cost, is the principal mechanism behind the proposed model. The variation between independent factors of crude oil price and refinery cost will define how much biodiesel can be produced in an economically profitable manner, if it were to be a free market scenario.

Figure 1 shows the global biodiesel fuel blend limits at various ‘crude oil price-refinery cost’ combinations. It is established that a maximum fuel blend level of 9.24% is possible, when the crude oil price is high and refinery cost can be reduced substantially. In fact, if the glycerol co-product could offset the refinery cost completely, crude oil price of USD 129 per barrel will allow the maximisation of global biodiesel production. This is a plausible scenario as the all-time high crude oil price of USD 133.90 per barrel, exceeding the USD 129 per barrel mark.

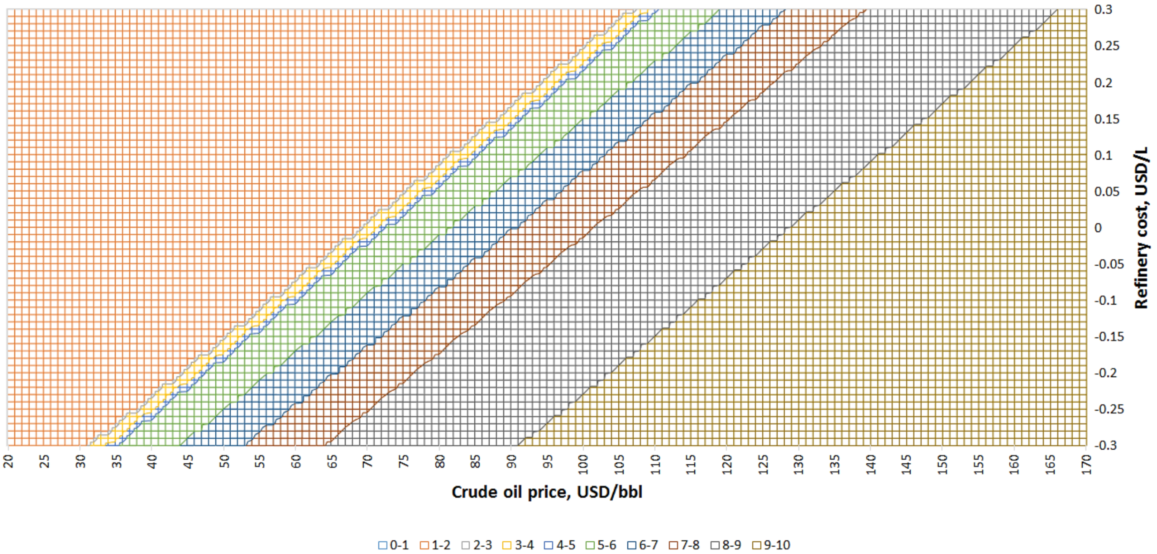

Figure 1: Global biodiesel fuel blend limits at different crude oil prices and refinery costs

It is observed that the plausible biodiesel blend levels follow a linear relationship where the ratio of crude oil price and refinery costs is 125 L per barrel. This for the entire crude oil price and refinery cost domains of USD 20-200 per barrel and USD -0.3 to 0.3 per litre of biodiesel produced, respectively. However, the fuel blend bands are not consistent, with the 2-5% blend level showing the narrowest band, where a variation of USD 4 per barrel of crude oil would result in a 3% change in plausible biodiesel blend levels. This suggests that it would be much easier to implement mandates to increase biodiesel blend levels from 0% to 5%, than it would be to increase from 5% to 10%.

3.2 Global Potential for Biodiesel Production

The current biodiesel production volume calculated from our model (as shown in Figure 2a) indicates that there are only a few major biodiesel-producing countries, such as Ukraine, Italy, United Arab Emirates (UAE), the United States of America (USA), China, Ireland, Bulgaria, Czech Republic, New Zealand, Paraguay, Honduras, Serbia, Uruguay and Norway. Each of these countries have at least a national production of 5,000 barrels of biodiesel per day.

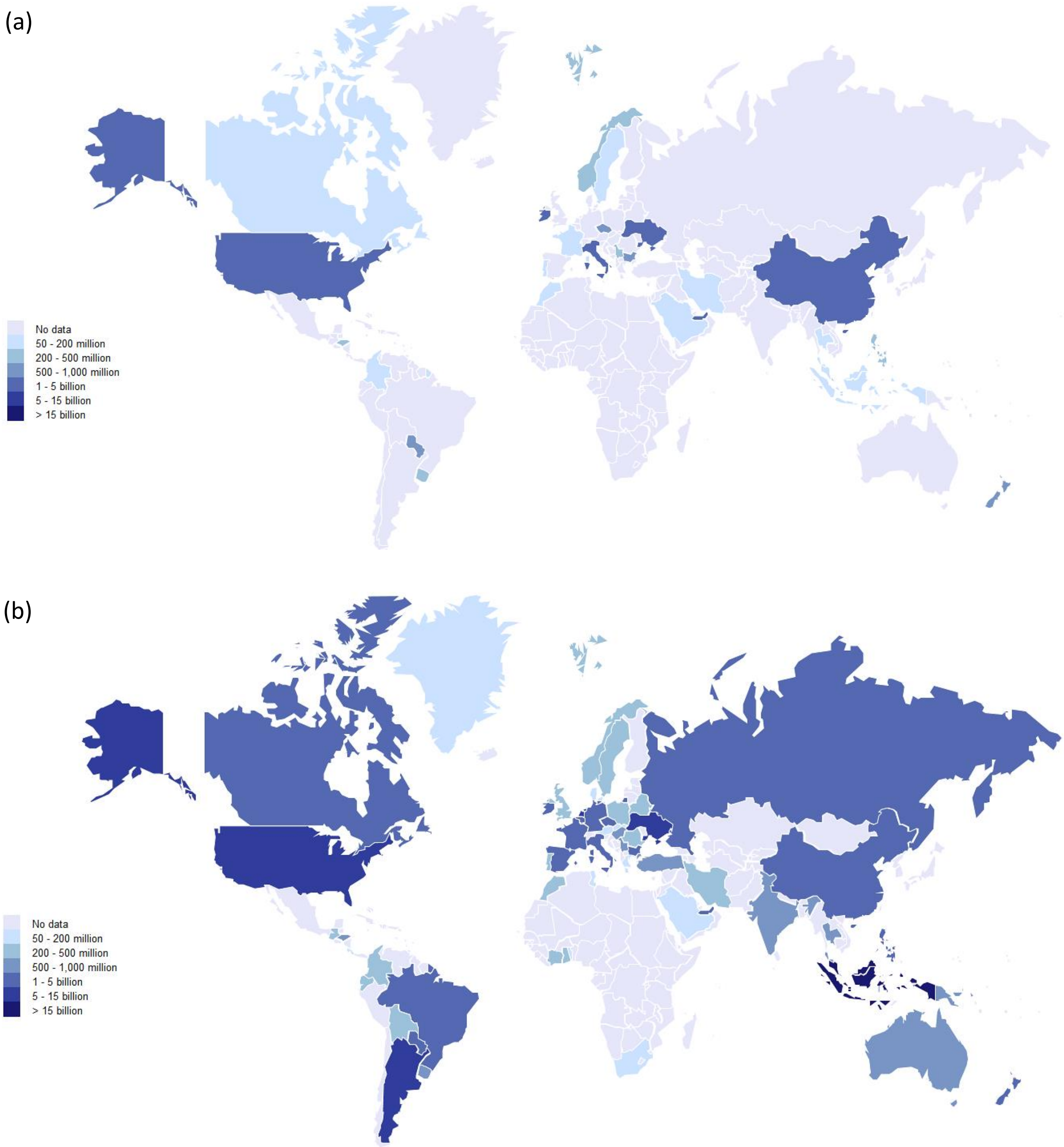

Figure 2: (a) Current and (b) maximum biodiesel production volume

However, many countries across most continents have great potential for large volume biodiesel production as illustrated in Figure 2b. Eleven countries such as Indonesia, Malaysia, the Netherlands, Ukraine, Canada, Argentina, Russia, Spain, the Philippines, Australia and India have immense potential for additional production of biodiesel exceeding a billion litres per year. The vast availability of excess, non-domestic palm oil feedstock allows the Southeast Asian nations, Malaysia and Indonesia to have the potential of producing up to 17.5 and 22.3 billion litres of biodiesel annually. This brings the number of countries with current and potential annual biodiesel production volume exceeding one billion litres of biodiesel, up to 20 countries.

When regions are considered, it seemed that Southeast Asia region would have the additional greatest potential for biodiesel production due to the propensity for palm and coconut to be grown there. Among the top 20 nations with biodiesel potentials, nearly half is concentrated in Europe with nine, Asia having six countries, the Americas having four countries and one from Oceania. This leaves only Africa not having the existing potential. However, as a large part of Africa is situated along the Jatropha latitude belt, the region can potentially be used to cultivate second generation biodiesel feedstock from Jatropha.

Figure 3 shows the maximum biodiesel blend levels achievable for each country, with respect to the level of diesel fuel that can be replaced. It is found that biodiesel can potentially replace all diesel consumption (B100) for three countries, Malaysia, Ukraine and Papua New Guinea if the economic climate is favourable to biodiesel production. These countries are shown above the blue line in Figure 3, while countries in between B10 and B100 is in between the red and blue lines region, B1 and B10 in between the grey and red lines region, and countries not having potential above B1 will be below the grey line.

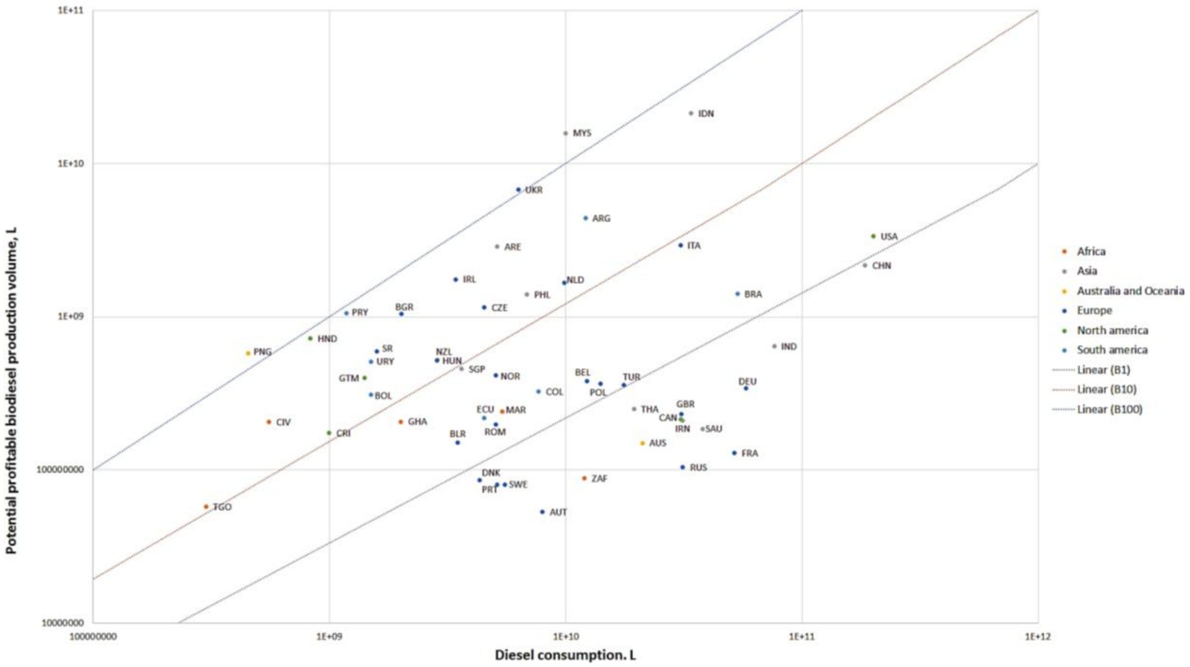

Figure 3: Maximum biodiesel blend levels achievable for each country

Clearly, there are 18 countries that have potential for biodiesel to replace 10-100% of their diesel consumption, 14 countries between the B1 and B10 replacement level, and 16 countries that have potential but only below 1% diesel replacement level. It is more likely for nations with smaller economy to replace a large proportion of their diesel consumption with biodiesel. This causes countries like China and Indonesia with their vast potential of biodiesel production volume to not have the ability to replace their diesel consumptions with locally sourced feedstock, due to the high diesel usage.

3.3 Onset of Biodiesel Profitability

Figure 4 shows the lowest possible crude oil price at which biodiesel will become profitable for the required replacement level. There are 25 countries that have the ability to replace at least 5% of diesel consumption, with Ghana being the country that can achieve it when crude oil price is as low as USD 63 per barrel. With the exception of Austria, all of those countries could reach the 5% level between USD 63 and USD 123 per barrel.

Among Southeast Asian nations, there are four countries that could meet the B5 supplanting level such as Indonesia, Malaysia, Thailand and the Philippines at the minimum crude oil price of USD 80, 82, 82 and 94 per barrel. This also means that between October 2010 and November 2014, these countries would have managed to make profitable biodiesel all the way up until B5 level.

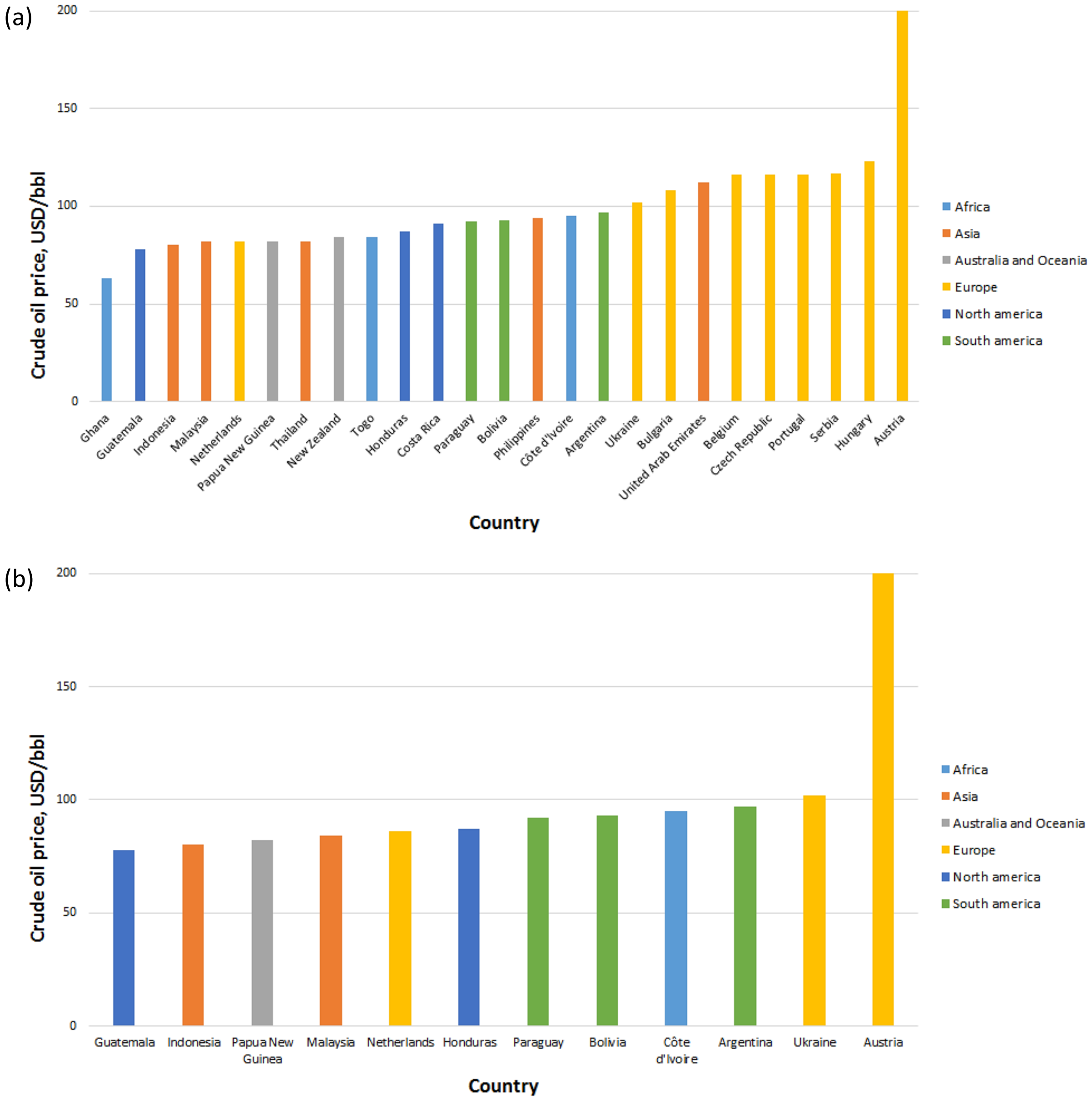

Figure 4: Onset of crude oil price for biodiesel to achieve (a) 5% and (b) 20% in fuel blend

If the target replacement level is fixed at B20, then only 12 countries would be able to achieve it, as shown in Figure 4b. The reduction in number of countries would be due to the availability of feedstock. Europe would only have three countries that could achieve B20, as compared to nine countries if it were to be only B5 replacement level. On the Southeast Asia front, only Indonesia and Malaysia could increase its biodiesel fuel blend from B5 to B20.

Indonesia is able to increase the biodiesel blend levels while keeping the same required crude oil price of USD 80 per barrel, while Malaysia would have to increase the minimum crude oil price to USD 84 per barrel. No other Asian country outside of Southeast Asia would be able to sustain a national-level B20 blend. The geographical spread of the countries that can meet the B20 demands is far-ranging with the remaining countries coming from Africa (one), Oceania (one), North America (two) and South America (three).

The continent-level weighted average minimum crude oil price to achieve the B1, B5, B10 and B20 levels is shown in Figure 5. The crude oil price changes with fuel blend requirements due to a variety of conflicting cases. Crude oil price required increases when more expensive feedstock is required for the rising blend level. Conversely, the crude oil price requirement can be decreased with the removal of countries with cheap feedstock, but do not have the volume.

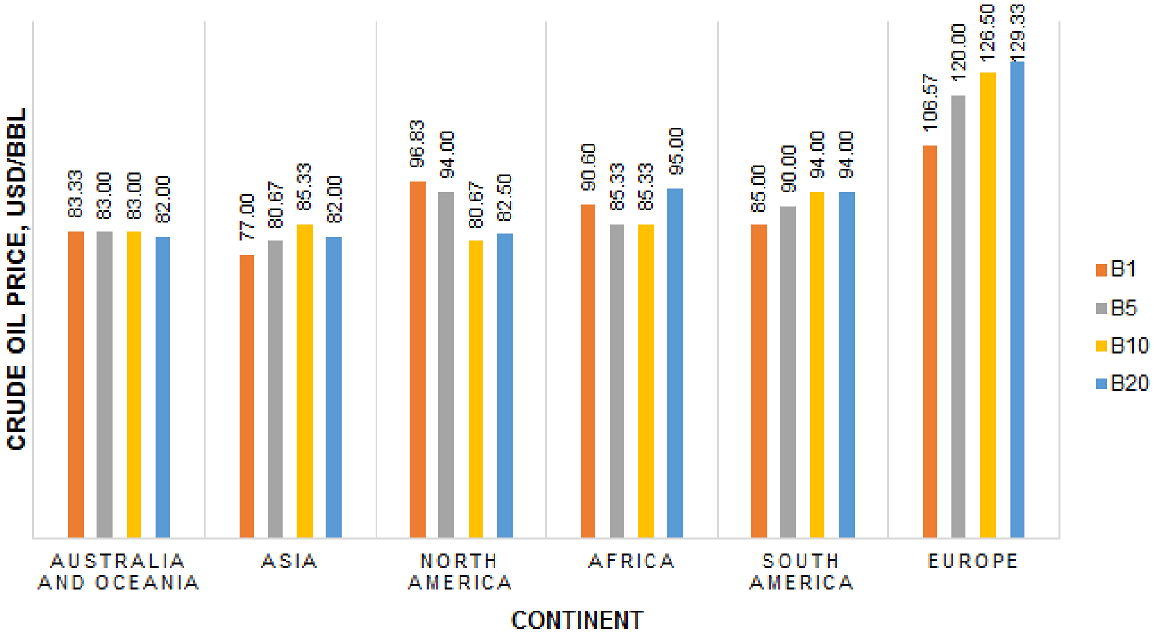

Figure 5: Continent-level weighted average for the onset of crude oil price, at which biodiesel could achieve various blend levels

Europe requires the crude oil price to be around USD 106.57-129.33 per barrel on average, for any mandate on biodiesel usage to be profitable. Despite the high prices of crude oil required for biodiesel in Europe to achieve economical feasibility, the level of biodiesel production technology in Europe is relatively for refinery cost to be reduced. This holds the potential to push the high crude oil price requirement in Europe lower, to closer than that of other continents. The crude oil price requirements for the other continents to increase biodiesel blend levels to B20 are all below USD 100 per barrel, with the ranges for each continent to be Oceania (USD 82.00-83.33 per barrel), Asia (USD 77.00-85.33 per barrel), North America (USD 80.67-96.83 per barrel), Africa (USD 85.33-95.00 per barrel) and South America (USD 85.00-94.00 per barrel).

3.4 Potential Economical Impacts of Biodiesel to National Economies

The use of biodiesel can improve the energy security of a nation, as they do not need to fully rely on fossil fuel. The diversification of fuel can also be economically beneficial with 13 countries standing to gain at least 1% of Gross Domestic Product (GDP). Figure 6 shows the lowest possible crude oil price in order to achieve the 1% growth in GDP through conversion of excess crop oils into biodiesel.

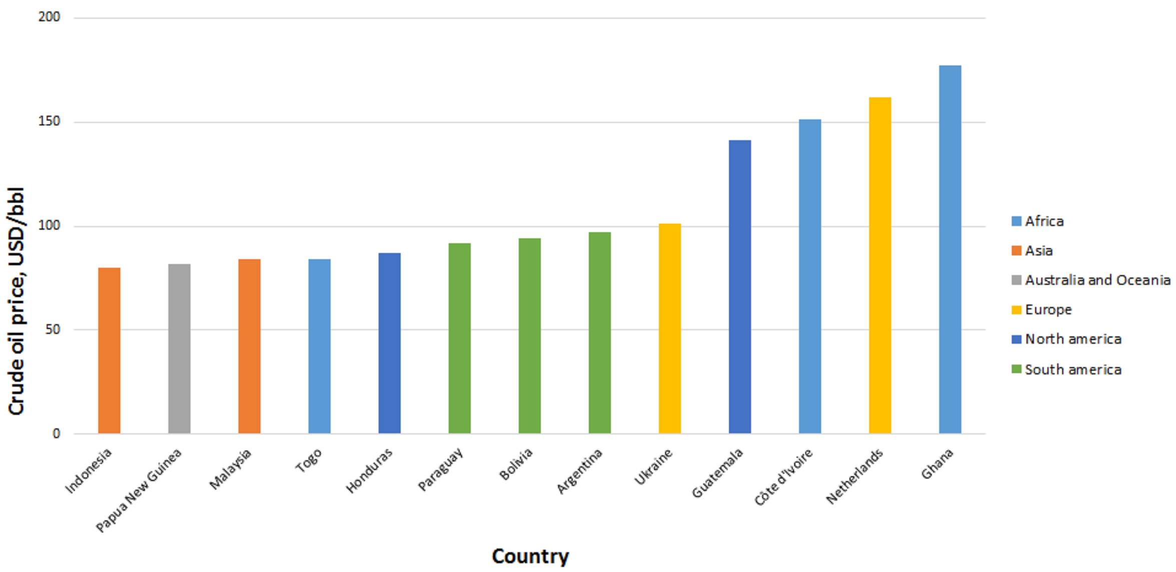

Figure 6: Onset of crude oil price for biodiesel to increase 1% of gross domestic products

Countries from Asia and Oceania, such as Indonesia, Papua New Guinea and Malaysia would be able to increase GDP by 1% through their domestic biodiesel industry, when crude oil price is relatively at USD 80, 82 and 84 per barrel. South American countries such as Paraguay, Bolivia and Argentina requires an overall higher crude oil price value in the range of USD 92-97 per barrel, as compared to those from Southeast Asia. Two European countries, namely Ukraine and Netherlands could also similarly grow their GDP by 1% if the crude oil price is above USD 100 per barrel.

It should also be noted that at lower GDP growth of 0.5%, there are 20 countries. Similarly, there are 37 and 45 countries if targeted GDP growth from additional biodiesel production is fixed at 0.10 and 0.05%, respectively. It was also observed that greater growth in GDP due to biodiesel production is more likely in developing countries, than in developed countries.

Figure 7 elucidates the potential change in GDP by percentage when crude oil price varies. This is modelled with the assumption that all excess lipids that were not domestically consumed can be converted into biodiesel. A total of 56 countries would have non-zero changes to their GDP when biodiesel is produced when crude oil price is high at USD 200 per barrel. Countries like Malaysia, Papua New Guinea and Indonesia could see a GDP growth by up to 10.36%, 7.67% and 5.57%, respectively. This makes these countries to have high potential for government mandates to develop large scale biodiesel industries or to enforce mandatory biodiesel fuel blending with diesel.

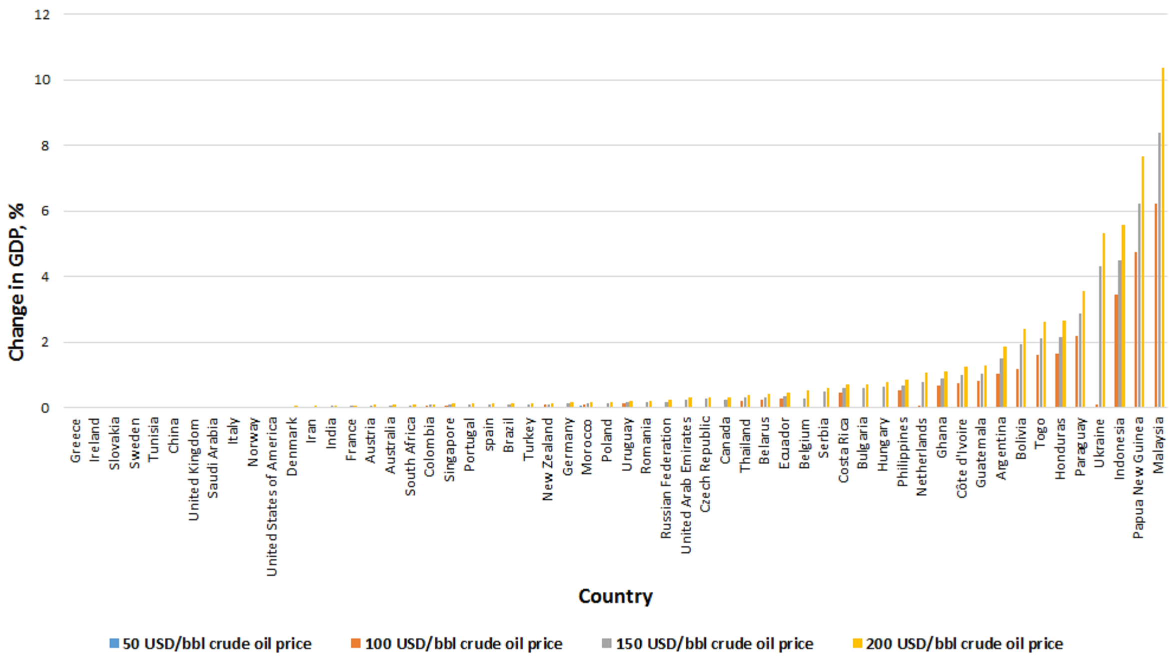

Figure 7: Change in GDP for each country at various crude oil price scenarios

3.5 Automotive Emissions

The level of blending of biodiesel into fossil diesel, will directly affect the level of exhaust-out emissions of NO, CO, UHCs, and PM, when used for combustion in automotive applications (Ng et al., 2012b). Figure 8 shows the potential change in the aforementioned emissions, in a scenario where the increase in crude oil price, creates an economical feasible condition to convert all potential available biodiesel feedstock into biodiesel used for automotive purposes. The exhaust-out emissions are also heavily dependent on the feedstock type, as all biodiesel feedstock contains different level of fatty acid methyl ester ratio, namely, the saturated fatty acid, mono-unsaturated fatty acid, and poly-unsaturated fatty acid methyl esters.

When the crude oil price is below USD 26 per barrel, it is not economically feasible to have any profitable biodiesel, hence the emissions remain the same throughout as shown in Figure 8. However, beyond USD 26 per barrel, a sudden change is observed in the level of emissions, due to Morocco being able to produce profitable biodiesel, as the country has the cheapest available biodiesel feedstock.

Majority of the countries can profitably produce biodiesel when the crude oil price is beyond USD 76 per barrel, where a sizable percentage change in emission level is observed, due to the cumulative contribution from multiple source of biodiesel feedstock. For the crude oil price range of USD 76-115 per barrel, emissions such as NO and CO has shown a fluctuation of increment and decrement within 0.5%. However, UHC and PM is observed to have a significant decrement of 0.7% and 4.4% respectively. This highlights the advantage of reducing harmful emissions through the adoption of biodiesel to supplant fossil diesel for automotive applications.

When the crude oil price increases beyond USD 140 per barrel, it is assumed that all feedstock available globally, are used to convert into biodiesel fuel, at its highest possible fuel blending ratio. Thus, feedstock availability becomes the limiting factor for percentage change in emissions, rather than crude oil price.

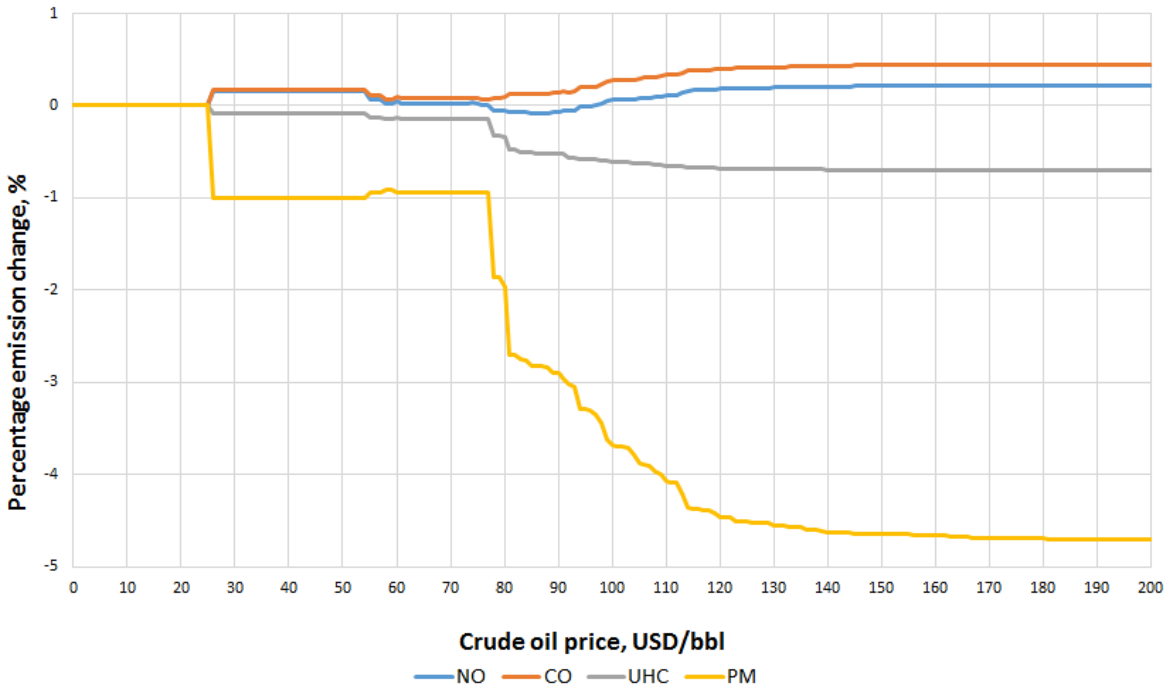

Figure 8: Potential global-scale automotive emission change against crude oil price, as compared to fossil diesel combustion scenario

4.0 CONCLUSIONS

In this study, a data driven predictive model was developed to evaluate the feasibility of biodiesel fuel implementation globally. Based on the model developed to determine the relationship of global fuel blend levels with independent factors, such as crude oil price and refinery cost, it is suggested that it is easier to enforce biodiesel blend mandates from 0% to 5%, as compared to mandating a further blend level increase from 5% to 10%. Southeast Asian countries show a significant potential to contribute towards an additional 40 billion litres of biodiesel annually. When fuel blending is being considered, out of 51 biodiesels producing countries, 43% of them can potentially achieve between the B10 and B100 replacement level, 25% of the country can replace 1-10% of diesel consumption, and the rest at below 1% diesel replacement level. However, when crude oil price and feedstock availability is compared at 5% and 20% fuel blend ratio, the numbers of countries that still retain the potential to replace diesel consumption reduced to 25 and 12, respectively, if crude oil prices ranging from USD 62-200 per barrel. The average crude oil price that is required to implement such biodiesel mandate, from 1-20% blending level, can be achieved below USD 100 per barrel for all countries, except for countries from Europe, primarily due to feedstock price. It is still potentially viable for European countries to produce profitable biodiesel at the higher crude oil price, when justified by a lower refinery cost through matured biodiesel processing technology. Besides, significant profit can be observed for these biodiesels producing country, up to a maximum of 10% increase in GDP, when analysed with different crude oil price. This should encourage government to support biodiesel industry, in the form of subsidies or incentives. In terms of environmental impact, the model can gain insight from the changes in emissions globally, affected by the economies of crude oil. Generally, the exhaust-out automotive emissions show a declining trend when the economy facilitates toward biodiesel production, although CO and NO is observed to have slight increment. Nevertheless, when filtered and optimized with commercial-ready feedstock, the results should reflect positively. In all, this model proves that there is high potential for biodiesel implementation globally, to improve energy security, generate income, and produce cleaner emissions for all nations.

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