IEA Bioenergy
Technology Collaboration Programme

Biofuels in Emerging Markets of Africa and Asia

An overview of costs and greenhouse gas savings

IEA Bioenergy: Task 39

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Biofuels in Emerging Markets of Africa and Asia

An overview of costs and greenhouse gas savings

Jean Felipe Leal Silva, Heitor Cantarella, Luis Augusto Horta Nogueira, Raffaella Rossetto, Rubens Maciel Filho, Glaucia Mendes Souza

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Executive Summary

This policy brief highlights the critical potential of biofuels in reducing greenhouse gas (GHG) emissions in the transportation sector. A previous report by Task 39 of the IEA Bioenergy TCP discussed the potential of biofuels in emerging markets of Latin America, and this report expands the study to countries of Africa and Asia: The People's Republic of China (hereafter China), Ethiopia, India, Indonesia, Malaysia, South Africa, and Thailand. Emerging markets are countries experiencing fast social and economic development, and their contribution to global GHG emissions is expected to rise fast. If this selected group of emerging markets were to have the same per capita CO_2 emissions in the transportation sector as OECD countries, global emissions of this sector would increase by 102%. This policy brief discusses three aspects of biofuel use in these countries as a tool to curb GHG emissions: 1) the potential GHG savings of sustainably produced biofuels; 2) the impact of biofuel on the final cost at the fuel pump; and 3) the capacity of biofuel production considering land use demand.

A life cycle assessment of biofuels reveals substantial reductions in GHG emissions for biofuels produced in Africa and Asia — up to 78% for biodiesel and 81% for ethanol compared to conventional fuels. These values are similar to those previously reported for biofuels produced in Latin America (up to 79% for ethanol and up to 84% for biodiesel). Notably, sugarcane ethanol in South Africa achieves an impressive 87% GHG emission reduction because of the high emission intensity of fossil fuels used in the South African market (which uses synthetic fuels produced via coal gasification and Fischer-Tropsch synthesis). To leverage these GHG benefits, replacing fossil fuels with biofuels is advised, particularly in circumstances and applications where electrification is difficult or only a longer-term option. To make sure that GHG savings are not partly or fully counteracted by direct or indirect land use change effects, countries should create and enforce policies to avoid that any agricultural activity, including bioenergy crops, are expanded into high carbon stock areas. Shifting from fossil to biofuels is challenging as well; however, implementing flex-fuel technology to allow users to seamlessly shift from fossil to biofuels is a reliable alternative to ease the energy transition in least developed countries where the installation of charging infrastructure for battery electric vehicles might be challenging. Biofuels are economically feasible in most countries except China and Malaysia. Despite this, they could still find a place through strategic imports (trade agreements) or subsidy policies related to biofuel blending mandates. India, Indonesia, and South Africa emerge as key beneficiaries, given the low carbon intensity of their biofuels and sulfur-related concerns mostly for diesel in Indonesia. While land demand is generally low compared to total country area, potential pressures for land use in China and Malaysia (for ethanol) could be addressed through international partnerships with countries that have better land availability for energy crop production, such as Brazil and the United States.

Key recommendations include restricting coal use, particularly in South Africa's synthetic fuel production and coal-based ammonia production and stimulating international biofuel trade as an alternative to fossil fuels. Country-specific comparisons of biofuel and electric vehicles should be considered, emphasizing the importance of biofuels in markets with high carbon intensity electricity. Lastly, the creation of policy schemes, akin to the Renewable Fuel Standard in the United States and the RenovaBio program in Brazil, is proposed to incentivize and reward low carbon intensity biofuel production, crucial for sustained expansion and fossil fuel displacement. This comprehensive report aims to guide policymakers in shaping effective strategies for a sustainable and greener transportation future for emerging markets.

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Energy Use in Countries of Africa and Asia

The worsening effects of the climate crisis have been prompting governments around the world to search for measures to reduce the dependency of their economies on fossil fuels. This is undoubtedly no easy task because of the correlation between energy use and socio-economic development [1]. **Figure 1** presents a summary of social, economic, energy, and environmental indicators of selected countries and regions that are mentioned in this policy brief [2]. These numbers indicate the inequality of wealth, energy use and greenhouse gas (GHG) emissions among different countries (or group of countries).

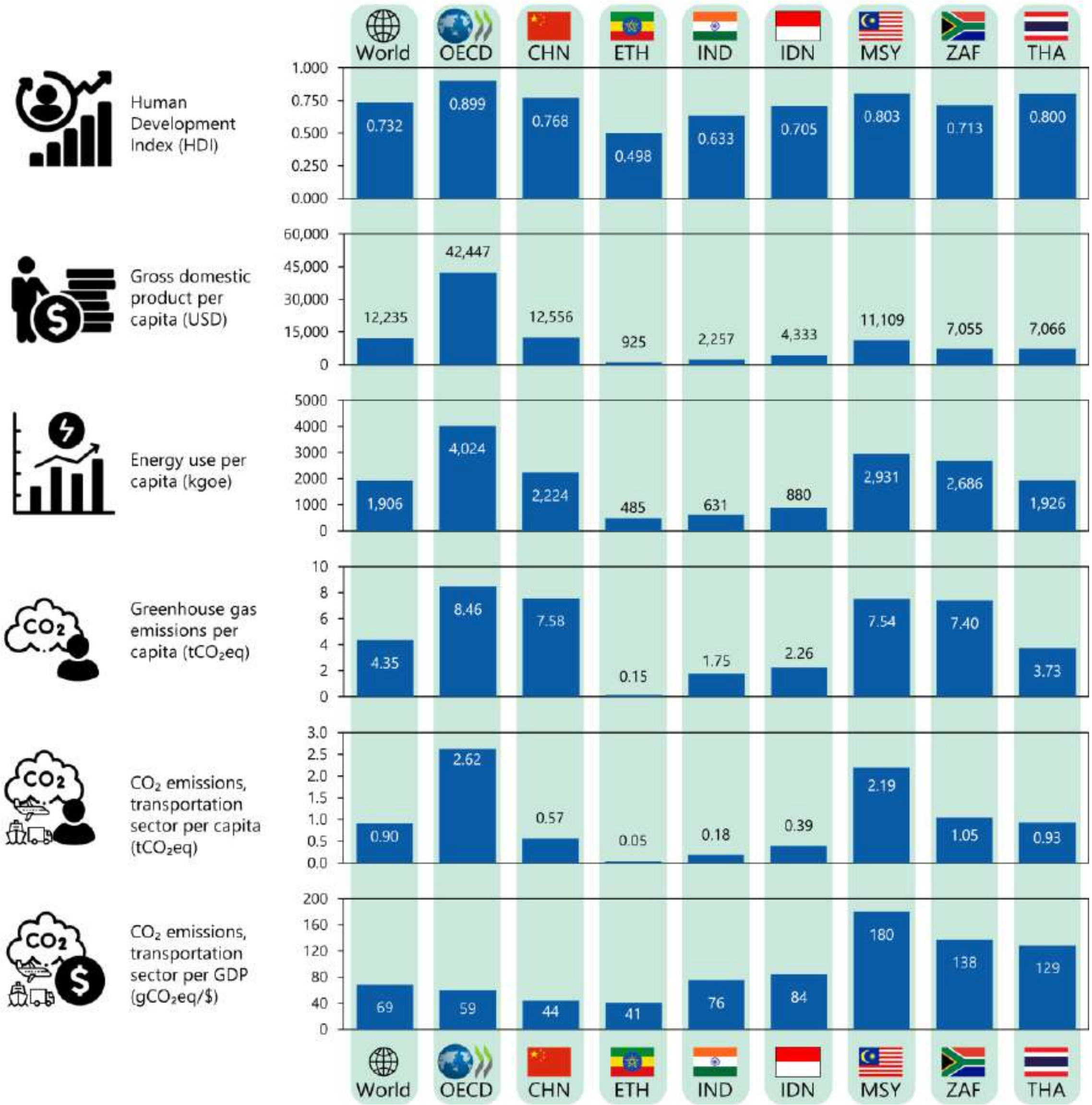

Figure 1. Summary of social, economic, energy, and environmental indicators of selected countries and regions according to data from the World Bank [2]**.** The graphs include data for the global average, the OECD average, China, CHN), Ethiopia (ETH), India (IND), Indonesia (IDN), Malaysia (MYS), South Africa (ZAF), and Thailand (THA).

These selected countries are emerging markets, which are countries that are in a state of fast social and economic development, and generally with fast growing population and energy demand [3]. In a previous study, the production of biofuels was assessed in four countries of Latin America: Argentina, Brazil, Colombia, and Guatemala [4]. The results showed the potential GHG savings when replacing gasoline and diesel by ethanol and biodiesel in these countries to be in the range of 37% to 84%. Regarding land use for expansion of production, the conversion of 5% of pastures in these countries is enough to double their biofuels production. Additionally, the production of biofuels in these four countries is energetically sustainable and economically viable in all biofuel pathways. These promising results are confirmed by the successful biofuel policies being expanded in these Latin American countries. Therefore, considering the importance of this strategy to reduce GHG emissions, this policy brief brings an expanded version of the study, now focusing on emerging markets of Africa and Asia.

The following group of emerging markets of Africa and Asia was selected: The People's Republic of China (hereafter "China", CHN), Ethiopia (ETH), India (IND), Indonesia (IDN), Malaysia (MYS), South Africa (ZAF), and Thailand (THA). Bearing in mind the looming effects of the climate crisis, these emerging markets need to avoid the mistakes of most developed markets whose wealth has been majorly developed at the expense of fossil resources, such as coal, oil, and natural gas. Despite their current state of development, these countries face challenges in replacing these sources of pollution. Therefore, immediate action is demanded from governments to avoid new developments based on increased demand for fossil resources to the best of their ability. According to Figure 1, the emerging markets selected in this study have a comparatively lower per capita gross domestic product and energy use compared to OECD countries, and most of them present values below the world average. This behavior is generally observed for GHG emissions as well. Also, when thinking of social development, all people should have access to energy to match their needs. In this context, if this group of emerging markets were to have the same per capita CO_2 emissions in the transportation sector as the average of OECD countries, global emissions of this sector would increase by 102%. As a matter of comparison, the total population of the seven emerging markets assessed in this report was 3.38 billion in 2021, while the total OECD population was 1.37 billion.

Transportation is key for socio-economic development in emerging markets. Despite the significant growth in electrification seen in the last years, battery electric vehicles (BEV) are still expensive for most of the population of emerging markets, besides investments in charging infrastructure competing with necessary developments in health, education, and basic services. Several studies have also demonstrated that the roll-out of electric vehicles requires a serious expansion of mining for critical materials and battery production capacity, and battery recycling is currently very limited and still needs further steps of development. On the other hand, life cycle assessment (LCA) studies have shown that internal combustion engine vehicles running on biofuels have lower GHG emissions compared to electric vehicles even when charging the vehicle using electricity of low carbon footprint [5]. Therefore, if a country has the option to produce biofuels, it is to be considered a major and immediately available option to replace fossil fuels. The electricity infrastructure to charge BEV is also a limitation in most developing countries.

Another aspect that needs to be considered is the existing vehicle fleet currently running on diesel and gasoline. These vehicles will stay in use for years to come since the average vehicle scrappage age is beyond 15 years [6], especially in emerging markets where purchase power is lower. In this situation, waiting for the natural fleet renewal is incompatible with the ambitions to tackle the climate crisis. Therefore, action is required to reduce the carbon footprint of the diesel and gasoline fuel pools as soon as possible, which can be achieved through biofuel blending mandates, as it is done in several countries. Nevertheless, before implementing biofuel policies, it is imperative to examine three aspects of biofuel production and use: 1) the potential GHG savings of biofuels; 2) the impact of biofuel on the final cost at the fuel pump; and 3) the capacity of biofuel production. The following sections of this policy brief will discuss these aspects and provide valuable information regarding the current market for fuels and biofuels in these countries and what actions need to be taken to reduce the contribution of the transportation sector to global emissions of GHG.

Current State of Biofuel Policies

Ethanol production in Africa and Asia was 5.2 PJ and 220.1 PJ in 2021, respectively (1 PJ is roughly equivalent to 23900 toe). These values corresponded to 0.2% and 9.7% of the global ethanol market, and their production was roughly equal to their total demand [7]. Also in 2021, Asia produced 533.7 PJ of biodiesel (32.6% of global production) and consumed 466.7 PJ of biodiesel (26.6% of global demand), thus acting as an exporter, mainly for Europe. At the same year, no significant production nor consumption of biodiesel was reported for Africa despite its great potential for fuel consumption and biofuel crop production.

Figure 2 presents the effective blending rate of biofuels in the gasoline and diesel fuel pool around the world [5]. Regarding blending policies, blends of ethanol are commercialized as EX, where X is the percentage of biofuel available in the blend — for instance, E10 in the United States. A similar strategy is used for biodiesel blends, commercialized as BX.

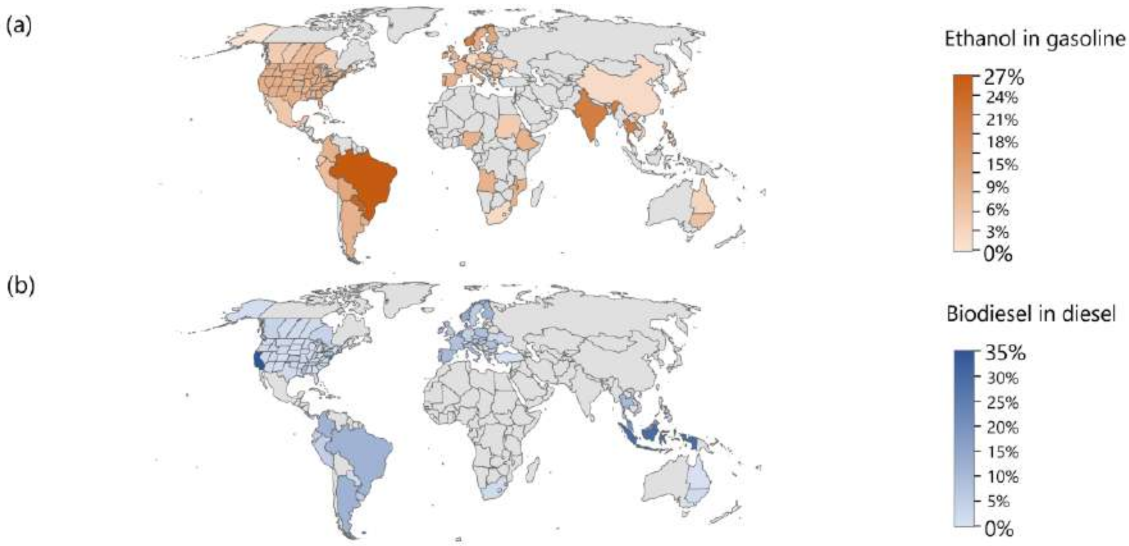

Figure 2. Blending rates of a) ethanol and b) biodiesel in their respective fuel pools across different countries, regions, states or provinces across the world, adapted from Cantarella *et al.*, 2023 [5]. Blending mandates are created by means of policies. In some cases, these policies determine minimum and maximum blending rates to allow some flexibility depending on market conditions. Therefore, these maps reflect the effective blending rate. In some countries, such as in Brazil, pure biofuel can be found in filling stations; despite replacing part of the demand for fossil fuel, this volume of biofuel was not considered as it requires vehicles with special technology (flexible-fuel vehicles). In general, there are several successful cases of biofuel use policies that contribute to reducing the use of fossil fuels. This model can be replicated in other areas of the world.

Ethanol is widely used in many countries as a means of reducing the carbon footprint of gasoline and as an antiknock agent because of its octane rating (108.6). Since the 1920s, tetraethyllead was the main antiknock agent used in gasoline, but use declined since the 1970s because of widespread lead poisoning. Tetraethyllead was largely replaced by MTBE (methyl tert-butyl ether). However, as a toxic water pollutant, this chemical needed replacement as well, and ethanol has been used as antiknock agent in most of the large fuel markets around the globe in blending mandates in small percentages. Additionally, improvements in air quality are observed in megacities when vehicles run on blends of ethanol. Examples include Tianjin (China) and Sao Paulo (Brazil) [8,9]. This is especially important considering the large number of megacities suffering from poor air quality in emerging markets such as China and India. Biodiesel's main appeal is its reduced carbon footprint; in addition, it contributes to engine lubricity and reduces soot formation. Besides that, biodiesel contributes to the security of the energy supply if domestic production of vegetable oil is possible, as in the case of Indonesia.

CHINA

China was the most populous country in the world up to mid-2023 when it was overtaken by India. The country has experienced fast economic and social growth in the past decades, with a substantial increase in the demand for fuels, which requires public policies to ensure security of energy supply. In 2017, China had established a program for nationwide adoption of E10 by 2020, but it was suspended because of prices of corn and the COVID-19 pandemic [10]. If successful, the annual ethanol demand would have risen to 19 million m^3. Existing or approved ethanol production facilities would cover only ~40% of this projected demand.

China was the fourth largest producer of biofuels in the world in 2021 after the United States, Brazil, and Indonesia. In 2022, China produced 2.4 million m^3 of biodiesel, mainly exported to Europe. Local consumption is low, with one reported B5 pilot program in the Hainan province [11]. In 2022, actual ethanol consumption in China was 3.8 million m^3, mainly produced from old corn stocks. Current consumption is mainly driven by E10 pilot programs in some areas of the country. Imports of biofuels are also unlikely because import tariffs (up to 70%) make imported biofuels too expensive to compete with fossil fuels. The 14th Five-Year Plan (2021-2025) of the National Development and Reform Commission of China presents goals for bioenergy development ranging from genetically engineered crops to use of sustainable aviation fuel. However, no blending targets were set [12].

ETHIOPIA

Ethiopia is an Eastern African country about twice the size of France. As a result of decades of fast economic growth, demand for energy is rising fast. Since Ethiopia is a landlocked country, it is interesting to guarantee security of energy supply using country resources, which can include bioenergy crops and biofuels. The government of Ethiopia has set goals to increase the use of biofuels to promote rural development, reduce the use of fossil fuels and diversify the country's energy mix. This is an important move considering the abundance of land and water resources in the country: the primary carbon production potential in Ethiopia is 4.5 t ha^{-1} y^{-1}, well above the global average of 3.4 t ha^{-1} y^{-1} [13]. Currently, only two sugarcane ethanol distilleries operate in Ethiopia producing 33 million L of ethanol and one plant produces biodiesel using castor oil. The country has an estimated 1.4 million ha of fertile land suitable for sugarcane production, and it has potential to produce 533 PJ of bioenergy [14], enough to fulfill Ethiopia's energy needs without compromising land for food crops.

INDIA

India has become in 2023 the most populous country in the world, and its economy has been steadily growing more than 5% per year in the last decades. The Indian National Policy on Biofuels, launched in 2018, has as main goal the reduction of petroleum imports. The policy was amended in 2022 to advance the deadline to reach the blending mandate target of 20% ethanol in gasoline by 2025–26 (before it was 2030), and to make other feedstocks eligible to produce biofuels [15]. Currently, the ethanol content of gasoline in India is 10%. Together with Brazil and the United States, India has launched the Global Biofuels Alliance for technology investment and collaboration as part of its ambitions to reduce reliance on fossil fuels. Policies enabling the production of flexible-fuel vehicles (using E85 instead of neat ethanol) have been established as well in Special Economic Zones and Export Oriented Units, besides other incentives to biofuel producers such as subsidies and tax breaks. A biodiesel blending mandate of 5% has been set for 2030. Current production can only achieve 0.1% of biodiesel blending, but this figure can change fast because of potential technology cooperation agreements inside the Global Biofuels Alliance. Currently, India relies on imports to meet its demand for vegetable oil, but policies have been established to increase domestic production of oil palm, rapeseed, soybean, and sunflower seed [16].

INDONESIA

Indonesia is the world's largest producer of palm oil, accounting for 59% of total production. The country is currently focused on developing its biofuel program to reduce reliance on oil imports, increase energy security and promote rural development. Most of the focus is currently set on biodiesel. Levies on oil palm exports are used to cover the spread between diesel and biodiesel prices [17]. While domestic demand for palm oil is increasing because of the biodiesel program, exports have been declining because of countervailing duties and regulations imposed by the United States and the European Union to dissuade the use of palm oil [18]. These include the European Union Deforestation Regulation.

In 2023, the blending mandate was raised to 35%. High biodiesel blends are rather unstable and may represent risks for engine use. Therefore, to further reduce the dependence on oil imports, the Indonesian government is considering hydrotreated vegetable oil (HVO), which is a drop-in biofuel produced via hydrocracking and isomerization reactions of vegetable oils in the presence of hydrogen. The Indonesian oil company Pertamina is planning to produce 290,000 m^3 of HVO in 2024 [18].

E5 started to be commercialized as an option in June 2023 [19]. Currently, Indonesia is investing in sugarcane production with the first goal of fully serving the domestic sugar market by 2028. Therefore, growth of sugarcane ethanol production in Indonesia will be limited in the coming years because ethanol will come from sugarcane molasses, which represents a small fraction of total sugars of this crop. On the other hand, two new corn ethanol plants of 300 kt/y capacity opened in 2023 [20]. Corn production is being incentivized through the distribution of subsidized corn seed, and it is planted as a second crop after rice. However, because of weather conditions and inadequate storage and handling of grains, corn in Indonesian is reported to have high aflatoxin content (beyond 20 ppb) [21]. Aflatoxins are poisonous mutagens and carcinogens. These aflatoxins are not destroyed during the corn ethanol process, and after distillation, they tend to concentrate in the distillers grains, a valuable co-product of the corn ethanol process used in animal feed.

MALAYSIA

As a policy to control inflation, Malaysia subsidizes diesel and gasoline by capping their prices. In 2019, RON95 gasoline in Malaysia had its price capped at about \$0.50 L^{-1} (value in United States Dollar, based on the original value — RM2.08 L^{-1} — and considering the 2019 exchange rate from Malaysian Ringgit) [22]. As part of the measures to reduce spending on subsidies, the Malaysian government implemented its own biofuel program. The focus is on biodiesel because the country has no significant production of cost-competitive crops for ethanol production. Malaysia is the second largest producer of palm oil, responsible for 24% of global output. As a low-cost feedstock, it is used to produce cost-competitive biodiesel. Malaysia is currently raising the blending mandate to 20%, a measure that has been postponed since the COVID-19 pandemic — despite this, the B20 blend was already in use since 2022 in some states [23]. As part of the program to foster palm oil production, the government collects a levy from palm oil producers. From this fund, 80% is used in research and development, 15% in biodiesel subsidies, and 5% in environmental protection. In fact, forest coverage in Malaysia, including naturally regenerating forests and planted forests, has been nearly stable in the last 10 years at 58% of total land area [24].

SOUTH AFRICA

The South African Biofuels Regulatory Framework established a target of 4.5% market share of biofuels in the fuels market, with a market share of 2% for first-generation biofuel technologies. The framework includes a feedstock protocol to regulate the production of biofuel crops so that the program does not compromise food security. Therefore, it bans the use of corn for biofuel production and stimulates the use of fallow land for biofuel crop production. The program set mandatory blends of E2 for gasoline and B5 for diesel to be started in 2015, but South Africa has been facing challenges to meet these targets [25]. South Africa has no significant oil reserves, and most of its fuel needs are obtained from coal, as discussed further. This information is key to understand the need to invest in biofuels production in South Africa.

THAILAND

The National Energy Plan of Thailand indicates a goal of reaching carbon neutrality by 2050 and net zero GHG emissions by 2065. Pricing schemes were created to encourage the market for vehicles compatible with E20 and E85 blends, which are gasoline blend rates available in the market together with E5 and E10. In 2022, ethanol represented 12.6% of the gasoline fuel pool [26]. The main feedstocks for ethanol in the country are sugarcane and cassava. Regarding biodiesel, Thailand currently uses B10. In 2022, because of high palm oil prices in the international market, lower rates were adopted. However, the Thai government has plans to increase the blending mandate to 20% in the near future because it increases the security of energy supply and reduces the emissions of particulate matter [27]. This is important because of targets for pollution recently set by the Thai government [28].

OTHER COUNTRIES

Kenya, Mozambique, and Nigeria are other African countries that deserve special attention regarding biofuel policy development. In February 2022, the government of Mozambique signed an agreement with Eni to develop projects to produce biofuels. Kenya has a well-established biogas program, with over 8,000 biogas plants and 17,000 domestic biodigesters. This project was implemented with the help of international organizations. Nigeria created a biofuel policy in 2007, but it failed to achieve the desired results. Nevertheless, incentives are being created recently to increase ethanol production in the country with the main goal of using it as fuel for cooking stoves to replace firewood. Angola is also planning to increase its biofuel industry, and the government expects to produce biofuels for domestic use and export before 2030. Currently, Biocom (an Angolan company) operates in the country and produces 33,000 m^3 of anhydrous ethanol per year and sugar in sufficient amount to supply 70% of the domestic market [29]. Malawi has already implemented an E20 blend, with all production coming from a single plant from EthCo (a Malawian company) that has been operating for the past 40 years.

In Asia, the Philippines and Vietnam also have great potential for biofuels production. In these two countries, wasted grain and crops could alone supply 6.6% and 11% of the total gasoline demand, respectively [30]. The Vietnamese government has issued policies to promote the use of ethanol blends in gasoline. Currently, E5 is used in the whole country. Besides the environmental benefits of ethanol, the local government developed the roadmap for ethanol use also thinking of security of energy supply [31]. Rumors that ethanol may damage vehicle engines were reported to be influencing the sales of E5 gasoline in Vietnam [32]. Despite the rise of vehicle electrification, the government should act upon these rumors through awareness campaigns because internal combustion engines will stay in operation for a long period, and these problems were observed only in older engines. In the Philippines, blending mandates have been implemented since 2009 and 2011: 10% for ethanol and 2% for biodiesel. About 50% of the ethanol demand is imported, 97% from the United States [33], because domestic ethanol production is limited to molasses yield from sugarcane processing.

Pathways to Biofuels

To fairly compare biofuels and fossil fuels in terms of cost and emissions, the analysis presented in this study considered the whole life cycle (from production/extraction to the energy harnessed in the internal combustion engine vehicle). The pathways to biodiesel and ethanol for the seven selected countries of this study (China, Ethiopia, India, Indonesia, Malaysia, South Africa, and Thailand) are presented in Figures 3 to 7. Additionally, the pathway from fossil resources to liquid fuel (gasoline and diesel) is shown in Figure 8. These figures show all the steps of the process and the boundary limits of the LCA and cost analysis. It is important to bear in mind that the CO_2 emissions produced during the combustion of biofuels represent biogenic carbon because they come from the atmosphere, whereas the emissions released when burning fossil fuels come from fossil reserves. Other emissions occurring during their production processes are indicated as well in Figures 3 to 8, as well as other process inputs considered in the LCA.

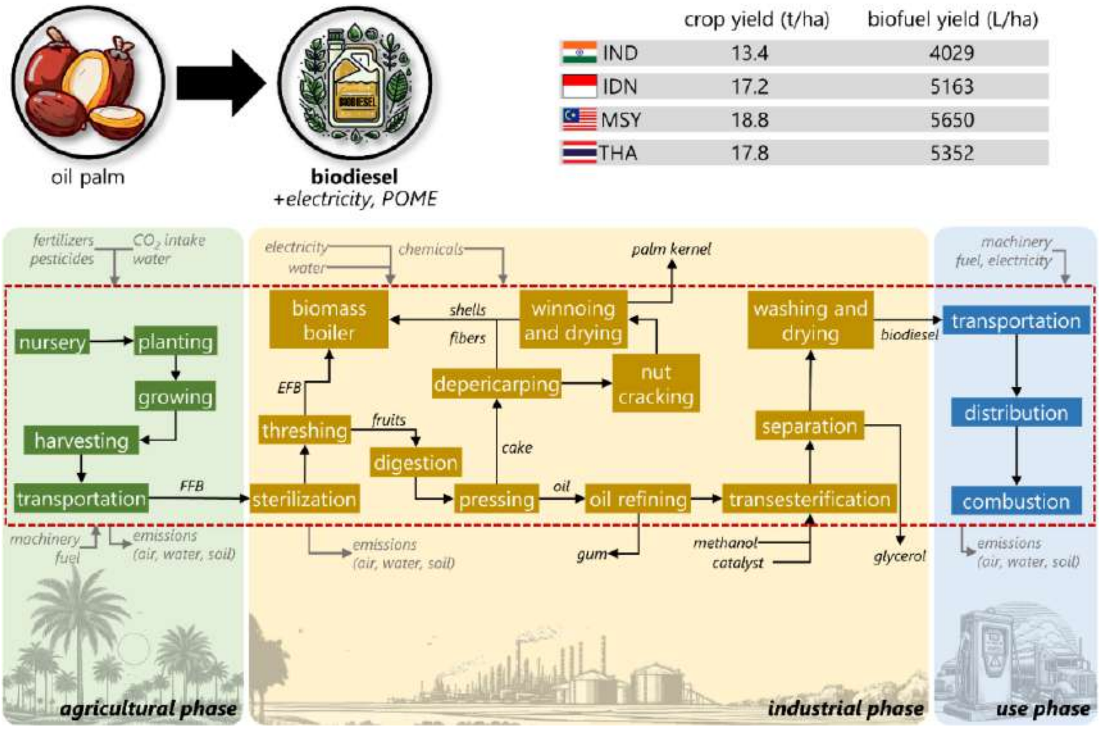

Figure 3. Pathway from oil palm to biodiesel and its crop and biofuel productivity in countries in which it was considered in this study.

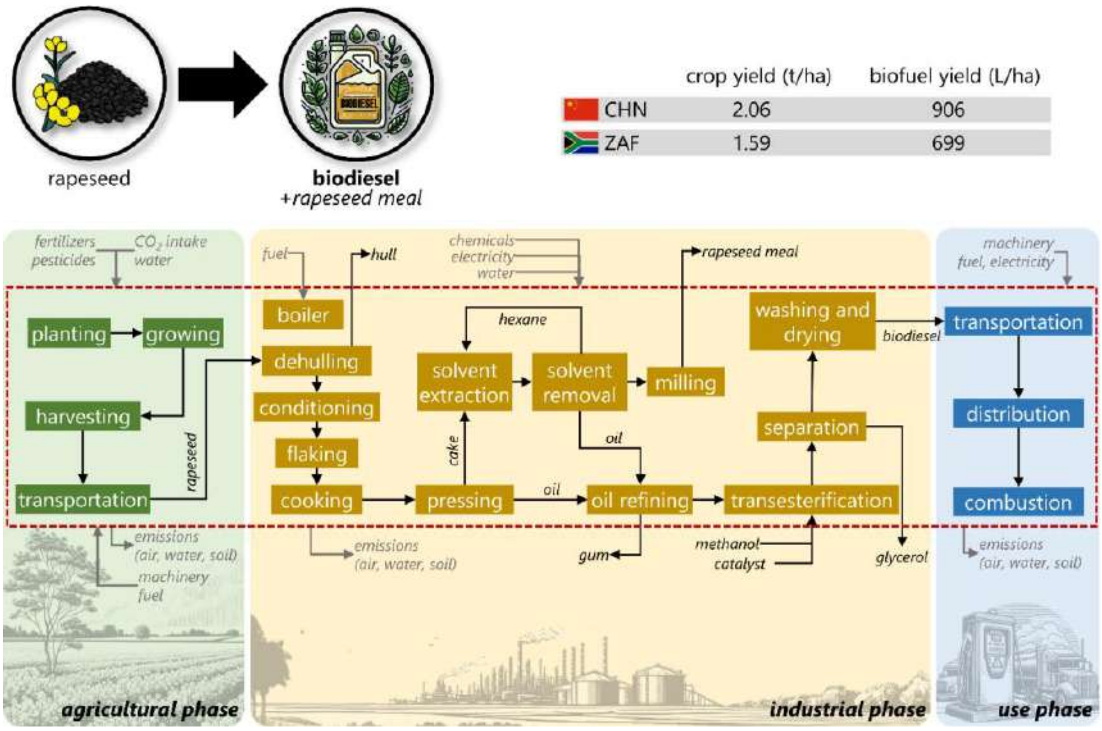

Figure 4. Pathway from rapeseed to biodiesel and its crop and biofuel productivity in countries in which it was considered in this study.

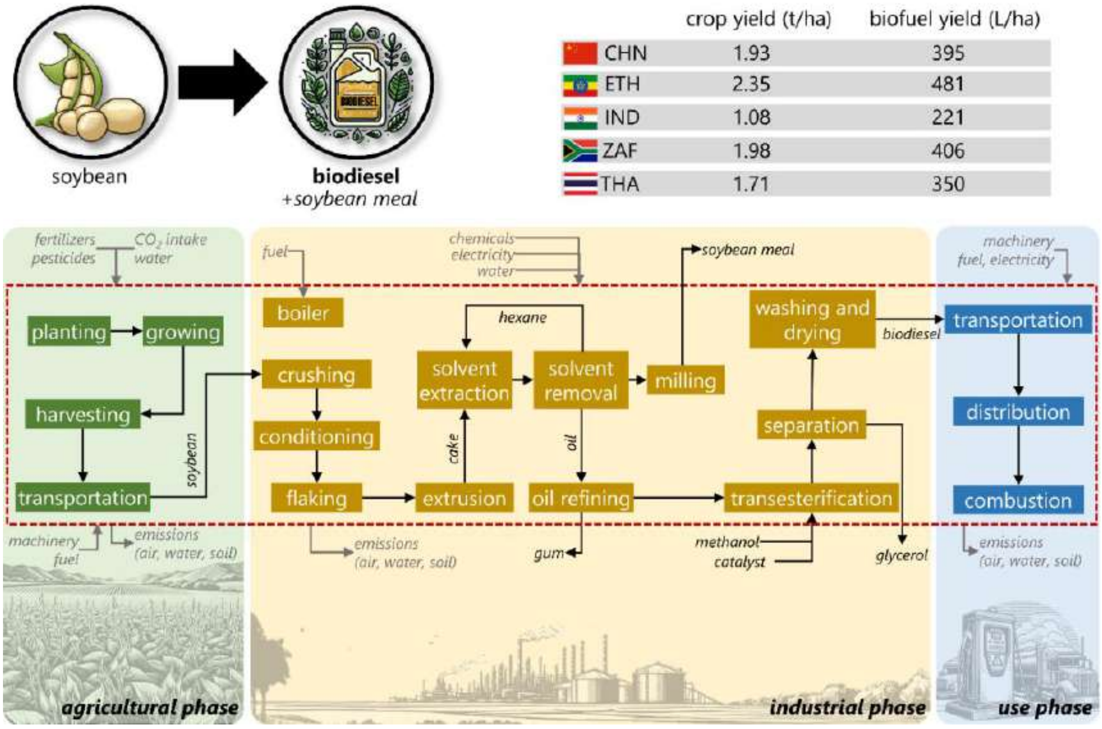

Figure 5. Pathway from soybean to biodiesel and its crop and biofuel productivity in countries in which it was considered in this study.

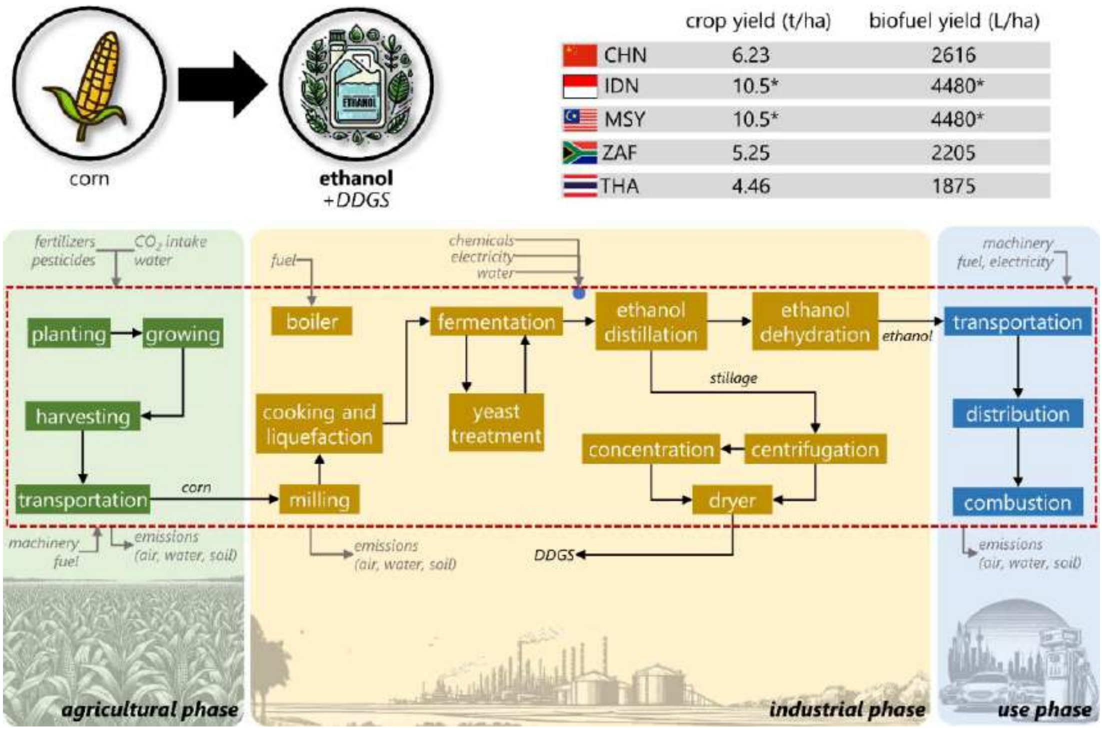

Figure 6. Pathway from corn to ethanol and its crop and biofuel productivity in countries in which it was considered in this study. "*": ethanol imported from the United States.

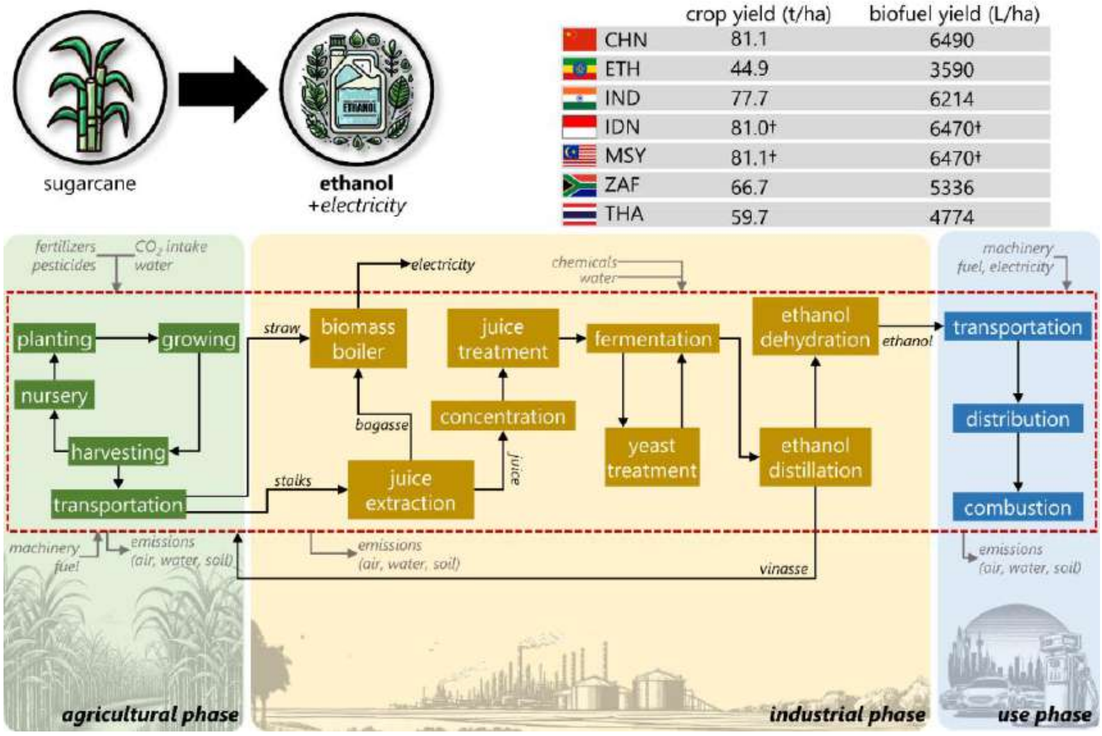

Figure 7. Pathway from sugarcane to ethanol and its crop and biofuel productivity in countries in which it was considered in this study. "†": ethanol imported from Brazil.

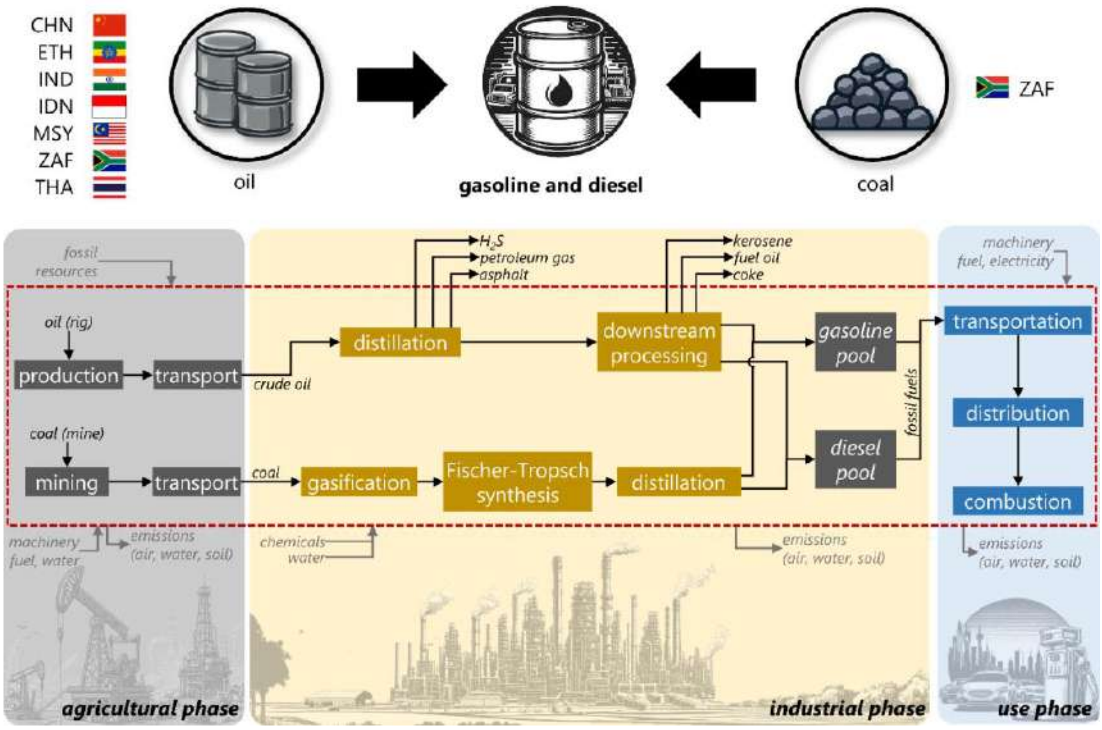

Figure 8. Pathways from fossil resources to liquid fuels considered in this study.

LCA of Biofuels in Africa and Asia

The global warming potential (GWP) of biofuels in each pathway is shown in **Figure 9** as a measure of the equivalent CO_2 emissions per unit of energy, based on the lower heating value of fuels and biofuels. Overall, all biofuels represent a decrease in global warming potential compared to fossil fuels. The most promising feedstocks are palm oil for biodiesel and sugarcane for ethanol. The better performance of these crops can be attributed to higher yields and the use of crop residues as renewable fuel for industrial processing of feedstock into biofuel, with an average industrial contribution of 5.7 gCO_2e/MJ to the total GWP. To make sure that GHG savings are not partly or fully counteracted by direct or indirect land use change effects, countries should create and enforce policies to avoid that bioenergy crops used in biofuel production are expanded into high carbon stock areas, as it is already foreseen in some existing biofuel policies. Moreover, in the case of palm oil biodiesel, mills must include anaerobic digesters to process palm oil mill effluent (POME). This step is important to avoid the emission of methane to the atmosphere, and it produces biomethane that can be used in industrial or farming operations of the mill or else it can be commercialized as an additional biorefinery product.

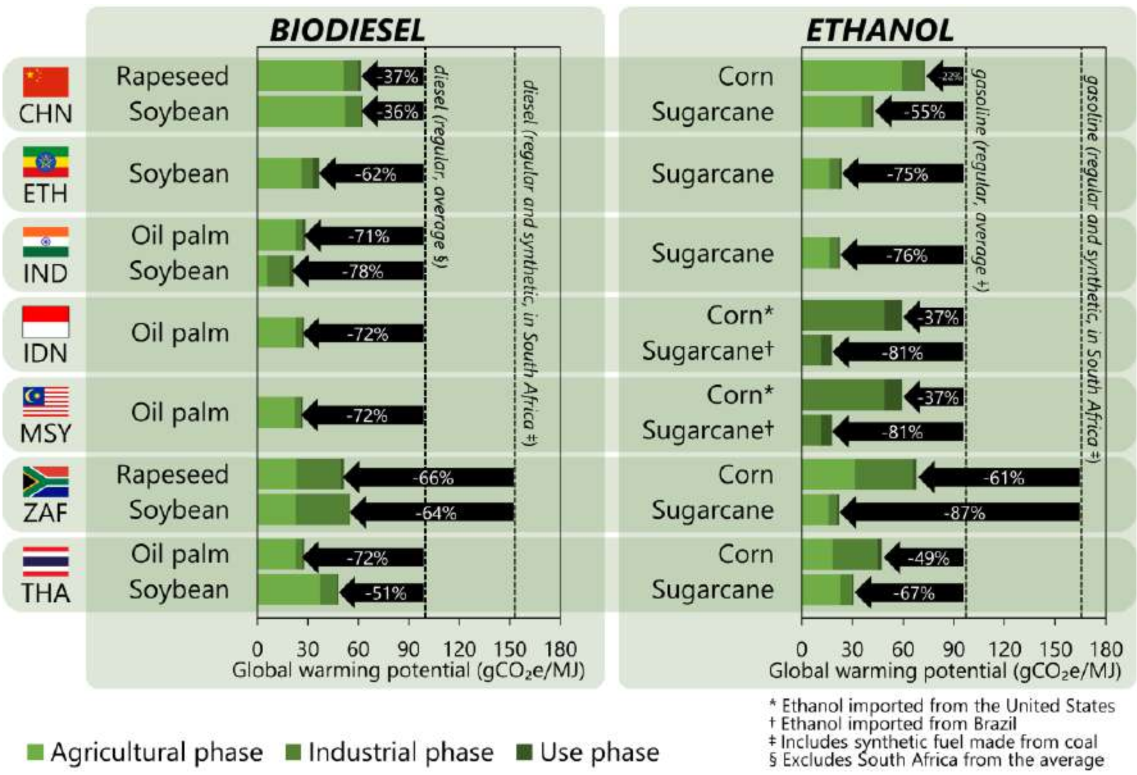

Figure 9. Results of global warming potential, in terms of gCO_2e/MJ of biofuels for each biofuel pathway. Results do not include impacts of land use change. Potential reduction in GWP was compared to the GWP of fossil fuels considering the average blend of synthetic (from coal) and regular fossil fuels (from oil) in South Africa or the average for regular fossil fuels in the other countries. The graph demonstrates the burden of the agricultural phase in the total GHG emissions of each biofuel pathway. The graph also presents the reduction of GHG emissions compared to the emissions produced when burning the same energy content of fossil fuel — which includes synthetic liquid fuels produced via coal gasification and Fischer-Tropsch synthesis in the case of South Africa.

Certain biofuel pathways in China and South Africa show GWP levels almost as high as regular gasoline or diesel due to fossil energy use in both agricultural and industrial phases. For instance, corn ethanol in China represents a decrease of only 22% in GWP compared to fossil gasoline because of the use of fossil energy during the industrial phase of ethanol production and emissions during the agricultural phase, mainly related to the use of coal-based ammonia. South African biodiesel processes, relying on coal, emit 49–54 gCO_2e/MJ during their agricultural and industrial phases. In these processes, replacing coal with natural gas in low NO_x boilers could reduce GWP to 38 gCO_2e/MJ (-26%) for rapeseed biodiesel and 34 gCO_2e/MJ (-38%) for soybean biodiesel, well below the GWP for fossil diesel in the country (153 gCO_2e/MJ). This value could be further reduced if biomass is used as boiler fuel. Replacing fossil fuels in South Africa can be seen as a low-hanging fruit in the fight against climate change, as part of their gasoline and diesel fuel pools are produced via coal gasification and Fischer-Tropsch synthesis (see box "*Coal-to-liquid and the Curious Case of South Africa*" below). Creating policies to curb coal use and encourage the use of biomass instead should be a top priority.

BOX: COAL-TO-LIQUID AND THE CURIOUS CASE OF SOUTH AFRICA

South Africa has almost no proven oil reserves. However, it has plenty of inexpensive coal. To achieve security of energy supply, South Africa's government incorporated in 1950 the South African Coal, Oil, and Gas Corporation, currently known as Sasol (an acronym of the name of the company in Afrikaans). The company's main business is using Fischer-Tropsch synthesis to produce synthetic fuels from coal gasification, in a process with very high GHG emissions.

Crude oil is composed of a mixture of hydrocarbons. In an oil refinery, this mixture of hydrocarbons is separated into oil fractions that are further processed via chemical reactions that break large molecules into smaller ones and adjust their properties, making these fractions suitable for use as chemicals and fuels (e.g., kerosene, gasoline, and diesel). Therefore, one can view oil refinery operations as "finishing touches" to crude oil since the molecules are already there. In the case of synthetic fuels produced via Fischer-Tropsch synthesis, similar hydrocarbons are produced as well (**Figure 10**), but they are synthesized atom by atom using syngas, a gas composed of hydrogen (H_2) and carbon monoxide (CO) that can be obtained via coal gasification. Liquid fuels produced via oil refining or Fischer-Tropsch synthesis produce about the same amount of GHG emissions when burned in engines. However, the big difference in their life cycle GHG emissions is mostly caused by GHG emissions during their manufacture.

As oil refining consists of separations and "finishing touches" to crude oil, almost all carbon of the original oil barrel is recovered as refinery products. On the other hand, in Fischer-Tropsch synthesis, coal is poor in hydrogen atoms; thus, these are sourced from water molecules. To obtain these hydrogen atoms, the oxygen atoms of water molecules react with the carbon from coal, thus yielding CO_2. For this reason, the production of 1 kg of synthetic hydrocarbons via Fischer Tropsch synthesis from coal gasification yields at least 5.5–5.9 kg of fossil CO_2. The energy requirements of the process are high, increasing its carbon footprint to 7.0–12 kg of fossil CO_2 per kg of hydrocarbons. Sasol is the only large-scale operator of this process in the world, and its Secunda CTL (coal-to-liquids) plant in South Africa emitted alone 57 million tonnes of

CO_2 in 2021. If it were a country, this single industrial site GHG emissions would be ranked 56° in the world, above countries such as Hungary, Ireland, and Portugal.

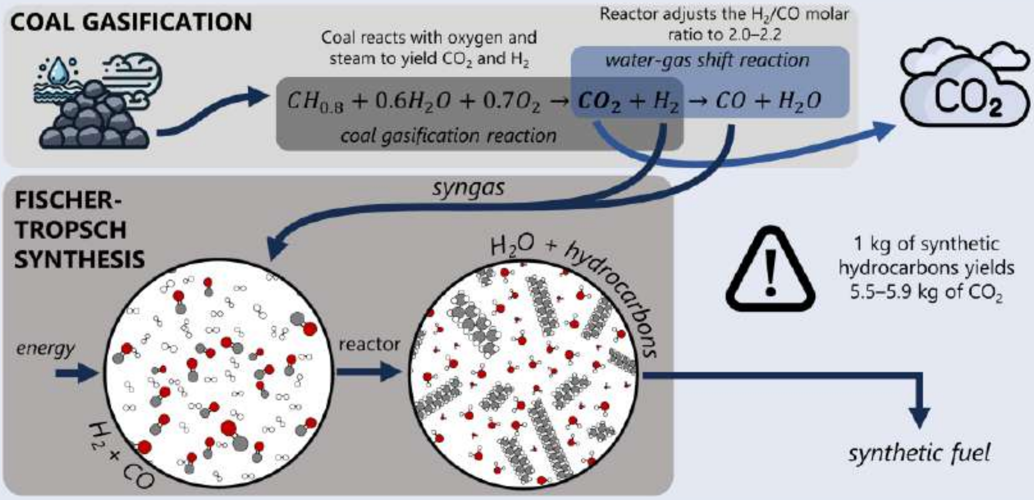

Figure 10. Coal gasification and Fischer-Tropsch synthesis to produce synthetic hydrocarbons. This process produces about 5.5–5.9 kg of CO_2 per kg of hydrocarbon — emissions related to coal mining and combustion of hydrocarbons are not included.

In China, nitrogen fertilizer use during the agricultural phase contributes 57%, 18%, and 27% to the total GWP in rapeseed biodiesel, soybean biodiesel, and corn ethanol production, respectively. This is mainly due to the use of coal-based ammonia, which has a GWP of 4.2 gCO_2e/g. This value is about 50% greater than the GWP of natural gas-based ammonia. Once again, curbing the use of coal and shifting to natural gas-based fertilizers or, even better, to biogas-based fertilizers, could reduce the GWP of the agricultural phase of the production of biofuels. Additionally, ammonia production could be tied to carbon capture, utilization, and storage (CCUS) technologies, thus yielding blue ammonia with a reduced carbon footprint. In the future, new green hydrogen developments might further reduce ammonia's carbon intensity to ~0.8 gCO_2e/g, pending large-scale demonstration.

An overview of the technologies for ammonia and nitrogen fertilizer production and their carbon footprint is shown in the box “Green Ammonia and the Carbon Footprint of Nitrogen Fertilizers” below. Fostering the development of blue and green ammonia technologies in countries like China through appropriate policies could enable worldwide production of not only biofuel crops but food as well, with a significant reduction in GHG emissions during the agricultural phase. Also, reducing N_2O emissions in soybean cultivation, which contributes 25% to the total GWP of soybean biodiesel in China, could be achieved by adopting the Brazilian model, using efficient N_2-fixing *Bradyrhizobium* strains with reduced use of synthetic nitrogen fertilizers.

BOX: GREEN AMMONIA AND THE CARBON FOOTPRINT OF NITROGEN FERTILIZERS

The carbon footprint of nitrogen fertilizers depends on the carbon footprint of the ammonia used in their production. Ammonia is produced via the Haber-Bosch process using nitrogen and hydrogen. Nitrogen is obtained via cryogenic distillation of air, while hydrogen can be obtained from various feedstocks (**Figure 11**), each with different carbon footprints. According to IRENA, 47% of the global hydrogen supply comes from natural gas, 27% from coal, 22% from oil, and 4% from electrolysis of water. Based on its sources, **hydrogen** is classified as **black** (from coal), **grey** (from natural gas and oil), or **green** (from renewable resources such as solar and wind power or biomass). The current production via electrolysis of water is not necessarily green because it depends on the electricity source. The carbon footprints of black, grey, and green hydrogen are 19—23 gCO_2e/g, 11—14 gCO_2e/g, and 1—4 gCO_2e/g, respectively.

The Haber-Bosch process for ammonia production is very energy-intensive. Besides emissions related to nitrogen and hydrogen production, energy-related emissions of the process make ammonia production a hot topic for net-zero targets and policies. Large reductions can be attained by banning coal as feedstock for hydrogen production (**black hydrogen**) or the compulsory use of CCUS technologies (**blue hydrogen** and **blue ammonia**). Ideally, the production of cost-competitive **green hydrogen** and **green ammonia** combined with renewable energy for industrial processes could drastically reduce the carbon footprint of nitrogen fertilizers used in the production of food, feed, and biofuel crops.

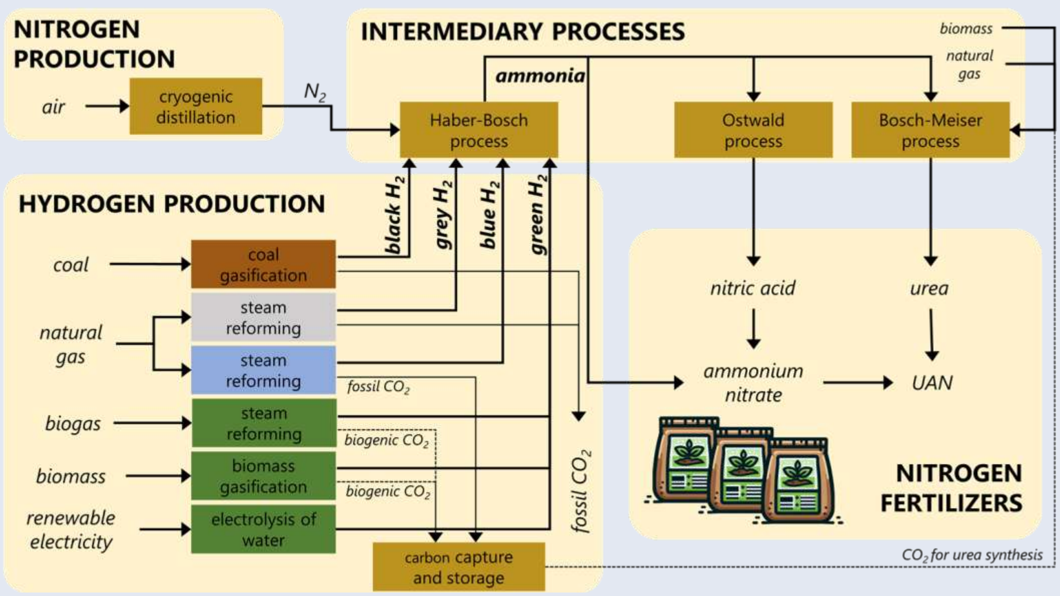

Figure 11. Routes to nitrogen fertilizers from nitrogen and hydrogen production. Nitrogen is separated from oxygen via cryogenic distillation, in an energy-intensive process. Hydrogen can be produced from various sources that lead to direct and indirect CO_2 emissions. Nitrogen and hydrogen are combined in the Haber-Bosch Process for the synthesis of ammonia. Ammonia is a key molecule to produce almost all nitrogen fertilizers, i.e., urea (via the Bosch-Meiser Process) and several ammonium salts. Another example is its oxidation to nitric acid (via the Ostwald Process), used to produce ammonium nitrate.

Pathways to ethanol in Indonesia and Malaysia show the potential for international trade of biofuels to decarbonize the transportation sector. Overseas transport contributes with 10 gCO_2e/MJ for corn ethanol and 6 gCO_2e/MJ for sugarcane ethanol, which accounts for 18% and 36% of the total GWP of imported ethanol, respectively. Despite this contribution, the overall GWP of imported ethanol represents a 37%–81% reduction in GHG emissions compared to gasoline in Indonesia and Malaysia, as shown in **Figure 9**. This model could be established via trading agreements among countries that are dependent on oil imports to meet their energy needs and countries with the potential for biofuel production.

Potential Cost of Biofuel Blends

The cost of biofuels in each pathway was analyzed and compared to the cost of fossil fuels in each country. In this phase of the study, some pathways were excluded because of their higher costs or higher GWP when compared to another biofuel option that is feasible in each country. For instance, in Thailand, soybean biodiesel costs twice more than palm oil biodiesel, and corn ethanol costs 80% more than sugarcane ethanol. A similar behavior was observed for soybean biodiesel in India, which costs 58% more than palm oil biodiesel. Corn ethanol was not considered in South Africa and China because of its GWP and competition with local food resources. Moreover, sugarcane ethanol has a better yield and lower environmental impact than corn ethanol.

Figure 12 presents the results of the economic analysis. The end consumer should bear in mind that biofuels in general have less energy content per liter. Therefore, it is important to compare biofuels both in terms of energy cost and the final price for the end consumer. We considered two scenarios: one representing a small departure from the current situation (scenario 1) and the other representing a high blending scenario (scenario 2). Scenario 1 corresponds to a blending mandate of at least 5%, and scenario 2 corresponds to a blending mandate of at least 25%. If the country already has a blending mandate, higher mandates were considered, as shown in **Figure 12**. Scenario 2 can be deemed as hypothetical because high blending mandates of ethanol and biodiesel demand engine adaptations (blends of 10-15% are considered feasible considering the currently existing fleet); yet this scenario can be seen as a means of measuring the impact of replacing fossil fuels. The results shown in **Figure 12** indicate that, except for China, the price at the pump is lower when adding biofuels considering the average fuel price from 2015 to 2022. This happens because of the lower energy density of biofuels: by adding biofuels to the mixture, the energy content of the blend will decrease compared to pure fossil fuels; since biofuels present in general the same or lower price in terms of energy content compared to fossil fuels (**Figure 12**), as the energy content decreases, the price per liter of the mixture will decrease accordingly. Reductions of up to 17% for ethanol in Thailand are possible. The blending of biofuels makes energy more expensive only in China and Malaysia — in the case of Malysia, biofuels compete with subsidized fossil fuels.

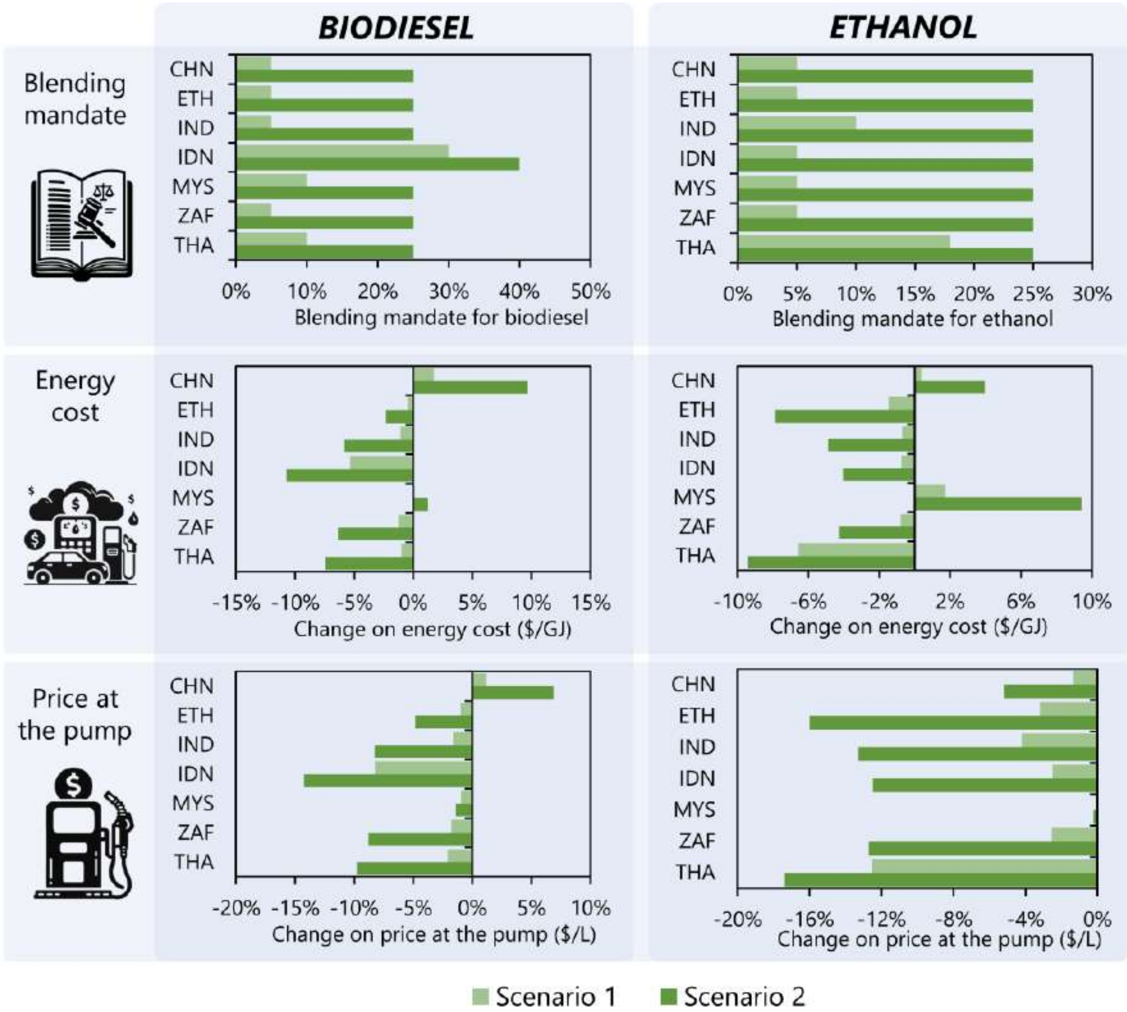

Figure 12. Percentage of biofuels assumed in scenarios 1 (at least 5% of biofuels) and 2 (at least 25% of biofuels) for blending mandates in each country and their impact on energy cost and price at the pump. The comparison of biofuel blends needs to include both the energy cost and the final price at the pump because stimulating biofuel usage depends on consumer's acceptance, which is directly linked to the cost of the fuel.

Another aspect to consider regards fuel economy: the lower energy content of ethanol decreases the energy content of the fuel blend and reduces the fuel economy (the relationship between distance traveled and fuel consumed by the vehicle). Consequently, when implementing blending mandates for biofuels, consumers will notice a decrease in fuel economy, which might prompt the rejection of biofuels. Therefore, making clear that this decrease also comes with a decrease in energy cost is fundamental to ensure the acceptance of biofuels by consumers. In Brazil, filling stations are required to show the percentage difference in price between E100 (neat ethanol) and E27 (gasoline), so consumers can choose based on the fuel economy of their vehicles.

Current Land Use and Demand

Land use is an important topic for the implementation of biofuels. This subject has been under scrutiny for a few years now, and the debate has led to criticism over biofuels production and use. Despite this, countries that rely on biofuels have demonstrated the effectiveness of these energy sources in reducing their GHG emissions [5,34–36] without impact their food security. **Figure 13** shows the current land use of each country considered in this study and the demand for land for each scenario of biofuel production.

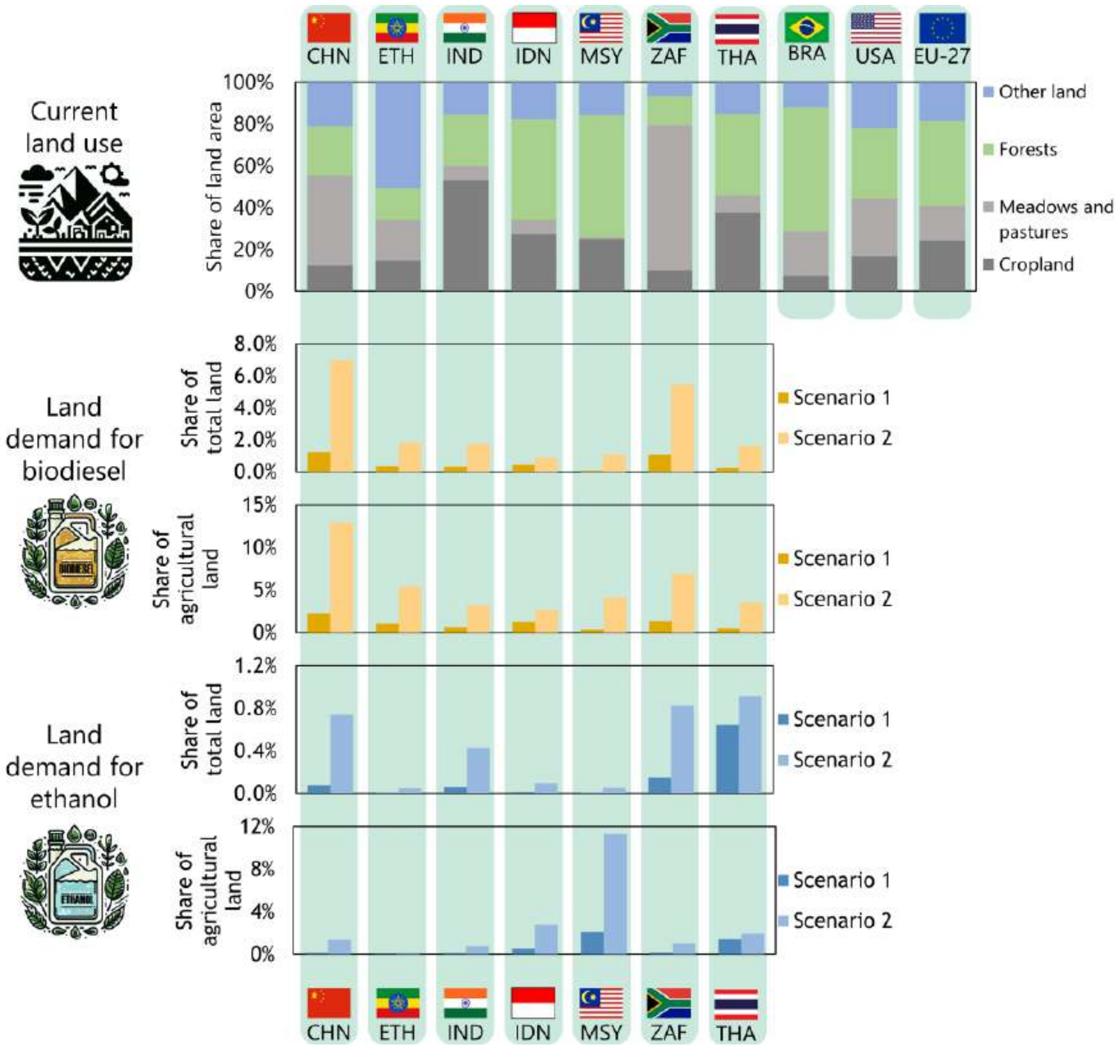

Figure 13. Land use for each country in 2022 and demand for land to produce biofuels in each scenario as a share of total land and agricultural land. Agricultural land includes land under temporary crops, land under temporary fallow, land under permanent crops, land under temporary meadows and pastures, and land under permanent meadows and pastures. Additionally, land use statistics for Brazil, the United States, and the European Union are shown as well. In the case of ethanol in Indonesia and Malaysia, the share of land area refers to land used in the ethanol-exporting countries (Brazil and the United States).

Compared to the total country area and agricultural land, the land demand to produce biofuels is rather low. The definition of agricultural land excludes forests and other land. In most cases, part of the land demand could be attained through the conversion of pastureland of low productivity to biofuel crops in systems that integrate biofuel and cattle production, for instance, as a measure of best management practices [4,37]. Demand in some countries could be too high considering the biofuel crops available, which would make unfeasible the blending mandate through domestic production. This is the case in China: because of its large population, most arable land is required for domestic food production. Therefore, because of potential competition with food, it is unlikely that biofuels from crops such as soybean and corn would be produced on a large scale. However, as it is being done in India, China also produces biofuels from old grain stocks unfit for food and feed use.

Biodiesel from palm oil has an outstanding yield, and sustainable intensification has led to small land requirements for countries of Southeast Asia to increase their production of biodiesel. Nevertheless, palm oil is criticized around the world because part of palm oil expansion (not only for biodiesel) since 2008 has happened through conversion of high carbon stock areas, leading to significant land use change emissions. In 2023, the European Union approved a plan to phase out imports of palm oil biodiesel because of the allegations that the production of this biofuel is indirectly linked to deforestation. At the same time, Indonesia and Malaysia, the largest producers of palm oil, have been working toward reversing the damage. Planted forest areas have been growing steadily in both countries, and peatland restoration projects focused on soil carbon restocking, fire regulation, and biodiversity recovery have been implemented [38].

GHG accounting via life cycle assessment is widely recognized as being robust and auditable. However, attributing values to potential effects such as indirect land use change is very challenging, and these effects cannot be securely measured or verified. Therefore, it is advisable to not include quantitative factors of indirect land use change in GHG reduction policies and, instead, promote a risk-based approach to avoid indirect land use change GHG emissions in the development of biofuel policies. Therefore, in the case of palm oil production, it is important that expansion of this crop focuses on sustainable intensification (with better varieties) and land expansion only happens on degraded areas or low productivity pastureland, and certification of sustainability is a key aspect to show compliance with sustainability criteria. As a suggestion, countries should create policies to rule out areas of high carbon stock for expansion of any agricultural activity, including bioenergy production.

As for ethanol, in most countries, land demand is rather low because of the outstanding yields of both crops considered for this biofuel: sugarcane and corn. Two exceptions are Indonesia and Malaysia. As explained before, this study considered these countries as examples to demonstrate the feasibility of the international trade of biofuels. The results in **Figure 13** for ethanol in Indonesia and Malaysia consider the required land area for ethanol production in the two exporting countries: Brazil and the United States. Overall, the impact of ethanol production for foreign markets in the supplier's land use demand is rather low.

Indonesia has established its ambitious biodiesel program to reduce the use of fossil oil and is a major importer. However, the country has difficulties in establishing ethanol production at the same pace because the main feedstocks for ethanol production are not available. Sugarcane cannot supply the domestic sugar market in Indonesia, and domestic corn has a high aflatoxin content. As mentioned earlier, aflatoxin contaminates the distillers grains, a co-product of the corn ethanol process used in animal feed. In Malaysia, production of these two crops is almost non-existent. One could argue that electric vehicles could be responsible for reducing the GHG emissions of the light-duty sector in these countries. However, considering that the electricity mix of these countries is mostly based on coal, it is unlikely that electric cars would be a better option compared to imported biofuels at the moment. Therefore, it is fundamental to encourage international trade of biofuels via trade agreements and policies. The box "*Establishing International Trade of Biofuels*" provides more key facts on this subject.

BOX: ESTABLISHING INTERNATIONAL TRADE OF BIOFUELS

Figure 14 shows the maritime routes for ethanol production considered in this study (from the United States and Brazil to Indonesia and Malysia). Currently, a large portion of oil is traded in the international market. Replacing these volumes of fossil energy with biofuels could reduce global GHG emissions. In the case of this study, overseas transport from the Americas to Southeast Asia contributed 6–10 gCO_2e/MJ to the total emissions of biofuels, representing about a tenth of the emissions related to burning fossil fuels.

Producing the necessary ethanol to establish a 25% blending mandate in China could utilize 1.7% of Brazil's and the United States' pastureland. This approach is appealing due to superior GHG savings compared to domestic biofuel production in China. The possibility of converting pastureland into biofuel crops, particularly in Brazil with predominantly grazing livestock, has been debated [37]. There's potential for Chinese investment in foreign biofuel production to decrease short-term oil import dependence. Additionally, investment in African countries to produce crops for biofuels could foster the development of agriculture techniques, which could enable increased food production in the African continent.

Figure 14. Potential routes for ethanol from producing countries (Brazil and the United States) to potential consumers (Indonesia and Malaysia), as assumed in this study, and another potential extension to China.

Potential for GHG Savings

Figure 15 shows the potential GHG savings that can be achieved by implementing biofuel blending mandates across these emerging markets when efficient processes are used, sustainability criteria are followed, and expansion into high carbon stock areas is avoided. A relative reduction of 10–15% can be achieved in most countries considering the blending mandates for scenario 2 (at least 25% of biofuels). This is a very promising result because the vehicle fleet of most of these countries will remain majorly based on internal combustion engine vehicles for years to come, and it represents an efficient way of curbing emissions using mature and affordable technology for these emerging markets.

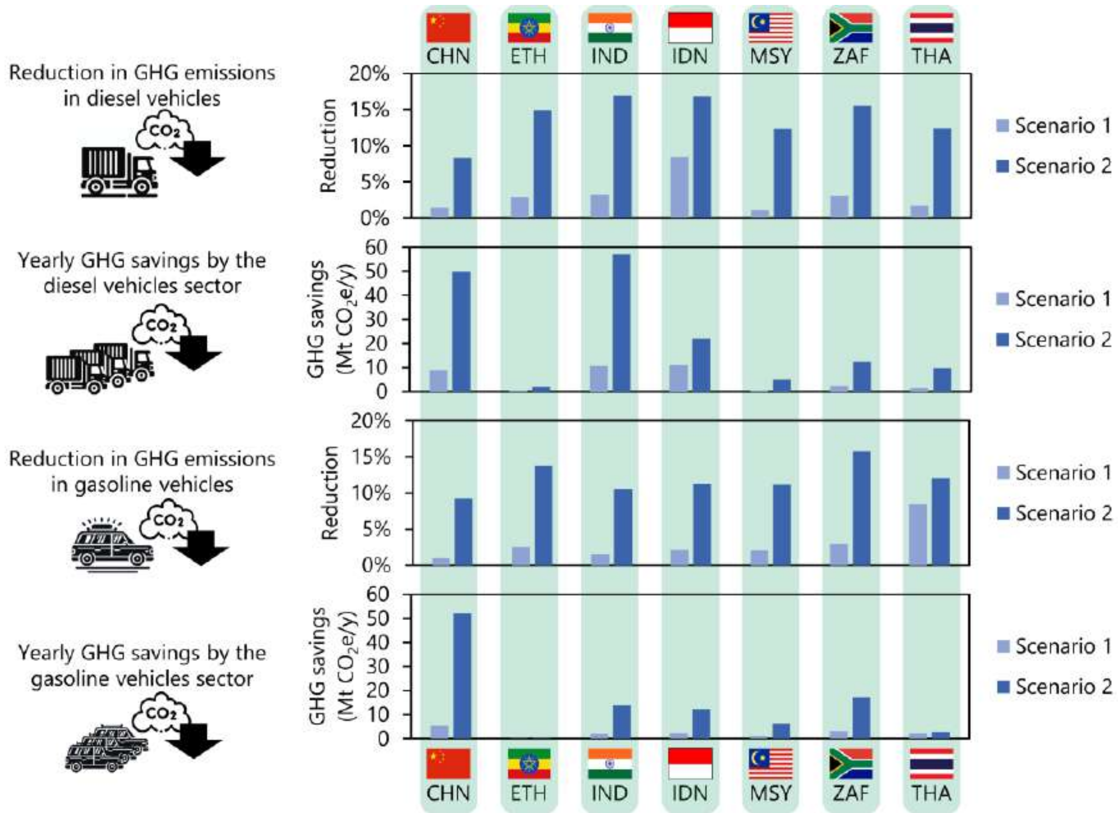

Figure 15. GHG savings by diesel and gasoline vehicles in the two scenarios of blending mandates. Scenario 1 represents a small departure from the current use of biofuels and Scenario 2 represent a hypothetical high blending scenario. Reductions in GHG emissions of about 10–15% are attainable using a 25% blending mandate in most countries. The best absolute reduction in GHG emissions by each sector was observed in China, which is the largest market among those considered in this study.

The potential for reduction in South Africa, considering both diesel and gasoline sectors, was estimated at about 30 Mt CO_2e. This value was calculated assuming displacements in the same proportion for both regular fossil fuels and synthetic fossil fuels produced via Fischer-Tropsch synthesis. However, if South Africa focuses on replacing exclusively synthetic fuels with biofuels, the impact can almost double. However, the proportion of synthetic fuels in the South African market is too high to be replaced solely with ethanol and biodiesel since these are not drop-in fuels. Indonesia has been considering the use of HVO diesel, which is a drop-in biofuel, to keep reducing its dependence on diesel imports. The same strategy could be used by South Africa to reduce oil imports and reduce the use of synthetic fuels.

Conclusions

Based on the current scenario for energy and fuels for transportation and the potential for biofuel production presented in this report for the selected emerging markets, some conclusions may be highlighted:

- Biofuel production was analyzed in China, Ethiopia, India, Indonesia, Malaysia, South Africa, and Thailand. Life cycle assessment of biofuels and fossil fuels indicated that biodiesel reduces GHG emissions by 36%—78% compared to regular diesel, and ethanol reduces GHG emissions by 22—81% compared to regular gasoline.
- A reduction of 87% in GHG emissions was calculated when comparing sugarcane ethanol to the gasoline used in South Africa (which contains synthetic gasoline produced via Fischer-Tropsch synthesis using coal syngas).
- These reductions are possible only when completely replacing fossil fuels with biofuels, with potential to produce less life cycle GHG emissions than electric vehicles. An easy transition away from fossil fuels could include the use of flex-fuel technology in vehicles, a mature and affordable technology for emerging markets. Otherwise, when used in blends with fossil fuels, reductions of 10–15% in GHG emissions from the transportation sector are possible without engine modifications in the existing vehicle fleet.
- These results do not include emissions related to land use change since this parameter comes with many uncertainties and soil carbon stock can decrease or increase where land is dedicated to biofuel crop cultivation. To make sure that GHG savings are not partly or fully counteracted by direct or indirect land use change effects linked to biofuel production, countries should create and enforce policies to rule out that agricultural activities (including bioenergy crop production) are expanded into high carbon stock land.
- Biofuels are economically feasible in the studied countries, except for China and Malaysia. In China, competition with food makes feedstock too costly. Nevertheless, in this case, biofuels could be imported. In the case of Malaysia, fossil fuels are subsidized to control inflation, and this policy could be extended to biofuels as well to make them economically competitive.
- GHG savings are very significant in India, Indonesia, and South Africa for different reasons. In India, biofuels can be produced with a very low carbon intensity. In Indonesia, besides the low carbon intensity of biofuels, fossil diesel has a high content of sulfur, which causes acid rain. In South Africa, despite higher-than-average emissions in the production of biofuels, they still represent a very large reduction compared to synthetic fossil fuels produced via Fischer-Tropsch synthesis.
- Land demand for biofuel production is low compared to each country's total land area and, in most cases, the agricultural area. However, it might pose pressure on cropland for food and feed purposes (in the case of China) or pastureland (almost inexistent in Malaysia). In this case, countries could rely on partnerships with other countries with more land availability so that they can implement their biofuel programs, with the condition that agriculture does not expand over areas of high carbon stock. Therefore, these partnerships should include international certification schemes.

Recommendations

- Create global restrictions on coal use. This should include ammonia production (used for fertilizer) and synthetic fuel production via Fischer-Tropsch synthesis (in South Africa). Despite the aspect of security of the energy supply that coal represents for South Africa, the production of synthetic fuels from coal has very high GHG emissions, and that country has great potential to produce biofuels. The use of biomass of dedicated energy crops or agricultural residues as a means of replacing coal to obtain syngas for the Fischer-Tropsch process may be a shortcut to reduce GHG emissions considering currently existing industrial infrastructure.

- Facilitate international trade of biofuels from countries with high domestic production potential to other countries and stimulate the use of the mechanisms and operating infrastructure already in use in the international trade of fossil fuels. Initially, large producers of biofuels such as the United States and Brazil should increase their production and aim at international agreements. Domestic supply of biofuels is not always feasible, and imported biofuels still present considerably lower global warming potential than fossil fuels — which are imported as well by many countries. Potential exporting countries in the Americas can expand their biofuels production without deforestation using existing pastureland of low productivity in integrated bioenergy and livestock production systems.
- Country-specific comparison between vehicles running on biofuels and battery electric vehicles is necessary for emerging markets considering their potential to produce biofuels and the forecasted growth of renewable electricity. Currently, even developed countries struggle to replace fossil electricity sources such as coal and oil. Among the seven countries analyzed in this study, six have electricity with carbon intensity beyond the 500 gCO_2e/kWh mark. Consequently, a shift from internal combustion engines to electric vehicles in these markets is hardly beneficial in the short to mid-term. Also, the current vehicle fleet will stay in use for years to come. Thus, gradually replacing fossil fuels with biofuels and adding drop-in biofuels to the diesel and gasoline fuel pools could represent a better solution to reduce the GHG emissions of the transportation sector of these countries. Meanwhile, governance measures should promote the expansion of renewable electricity and sustainable manufacturing of vehicles to avoid transport electrification compromising GHG reduction targets in the long term. Investment in public transport based on biofuels and/or renewable electricity should also be promoted as a means of reducing the number of car journeys, especially in large urban areas.
- Creation of policy schemes to promote and reward low carbon intensity biofuel production should be established. Examples include the Renewable Fuel Standard in the United States and the RenovaBio program in Brazil. These schemes increase the business case and long-term perspective of biofuel producers, and they are fundamental for those producers to expand their capacity and replace more fossil fuels. These policies should include transparent and auditable certification of sustainability criteria to increase financial rewards to the most sustainable biofuel production pathways, incentives for the use of pastureland and degraded areas, and restrictions on the expansion of bioenergy crops over high carbon stock areas.
- Considering the urgency of the climate crisis and how much GHG emissions have grown since the Paris agreement was signed, solutions with a greater technology readiness level and better fitness to the current infrastructure should be preferred and promoted to reduce GHG emissions in the short term. In parallel, policies should stimulate research to incentivize the maturation of biofuel processes using lignocellulosic feedstock as well, which is a strategy that has potential to produce biofuels with lower GHG emissions and increase the yield of biofuel by cultivated area.

Acknowledgements

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