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Biofuels technology

A look forward

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Abstract: This paper assesses biofuels technology readiness and provides foresight to biofuels development in Southern Africa. Efficient conversion pathways, coupled with biomass from waste or high-yielding energy crops, reduces both the costs of biofuels production and the environmental impacts. Currently, most biofuels are more expensive than petroleum fuels and market uptake will be influenced by mandates and subsidies. Advanced biofuels promise greater efficiencies and carbon emission reductions at reduced cost, but will require further R&D to reach commercialization. If developed appropriately, biofuels can reduce carbon emissions and improve energy security, while enabling sustainable agriculture and improved natural resource management.

Keywords: biofuels, bioenergy, technology maturity, technology readiness level, renewable energy, sustainable development
JEL classification: O1, O2, O3, O5, Q1, Q2

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1 Introduction

Biofuels, derived from biomass, include liquid, solid, and gas fuels, such as wood pellets, biogas, ethanol, and biodiesel, which are used to deliver renewable energy services in the form of heating and cooling, electricity, and transportation. There are various biomass sources that can be converted to biofuel products via thermochemical, physicochemical, and biochemical processes. For transportation, liquid biofuels are seen as the preferred route to easily replace current liquid petroleum fuels, since this incurs relatively little additional infrastructure cost, and offers an immediate route to decarbonize the transport system. However, the use of electric vehicles, hydrogen, and compressed biomethane are attractive alternatives to the current liquid fuels and internal combustion engines used in the prevailing transport system.

Biofuels can deliver benefits to society, such as: reduced greenhouse gas emissions, a reduction in the dependency on fossil fuels, and new opportunities for socioeconomic development. The global demand for biofuels is expected to grow rapidly because of mandates to reduce carbon emissions, and the escalating prices of finite petroleum fuels. Most of the growth is expected to come from the United States and the European Union, but many other countries also have biofuel mandates and targets that will drive biofuels demand and growth. The rapid increase in the global demand for biofuels over the next decade or more will provide opportunities for African exporters, because neither the European Union nor the United States is expected to be able to meet their consumption mandates completely from domestic production. In addition, African countries generally have abundant natural resources and high unemployment, and the cultivation of biofuel feedstocks therefore offers an additional income stream in rural communities and unique export opportunities. The domestic market for biofuels is also expected to be attractive in many African countries due to high fuel prices and energy security issues, as well as a rapid growth in demand. Southern African countries (with the exception of Angola) have limited oil reserves and import most or all of the oil needed to meet the region's requirements. For example, the South African proven oil reserves are about 2.4 billion litres, but at current production rates the reserves-to-production (R/P) ratio is only 0.23 years (Department of Energy 2012; Feygin and Satkin 2004; IEA 2014). Biofuels offer an alternative to petroleum fuels, thereby increasing the energy security and diversity of Southern Africa's liquid transport fuels, and reducing the dependence on imported fuels and volatile markets. Biofuels can also fulfil demands for heat and electricity, and thereby replace the unsustainable use of charcoal and firewood that occurs in many African countries. In addition, biomass and biofuels can be used to provide on-demand electricity to increase electricity access and security of supply.

Biofuel developments, however, can also bring a range of challenges and risks, including: potential land-use conflicts, environmental impacts, and risks to food security. There is considerable debate regarding whether biofuels contribute to or ameliorate problems such as land degradation, the depletion of water resources and soil nutrients, soil erosion, greenhouse gas emissions, air pollution, and biodiversity loss (Adler et al. 2007; Jordan et al. 2007; Stone et al. 2010). These complex interactions between agricultural activities, local ecosystems, and society require that bioenergy and agricultural planning and practices are integrated and effectively managed. If developed appropriately, sustainable bioenergy projects offer not only an opportunity for the production of renewable energy and the displacement of fossil fuels as energy sources, but also the development of more integrated and sustainable agricultural systems that are based on energy efficiency and improved natural resource management (de Vries et al. 2010; Hecht et al. 2009; IAASTD 2009). Therefore, the benefits of biofuels will need to be determined by considering technological, economic, social, environmental, and governance performance criteria in order to ensure that the widespread uptake and adoption of biofuels offers improvements over the prevailing fossil fuels, and contributes to sustainable development.

Implementing a Southern Africa-wide biofuel programme would be a long-term process that would be established over a period of many years, possibly only maturing a few decades into the future. Undertaking such a venture therefore needs to consider currently available technologies, but also the technologies that may be available in the near- and medium-term future. Changes in technologies may have profound impacts on the feedstocks available, and hence the production zones that are suitable for biofuel expansion. This paper assesses the research and development of biofuels technology, with particular reference to transport fuels in Southern Africa. It analyses the global and local developments in biofuels technology, as well as targets and trends, in order to assess biofuels technology readiness, and the stage of development to reach commercialization and widespread adoption. A comparison of the performance of various biofuels pathways was used to identify technology barriers that will need to be overcome in order to ensure that biofuels deliver low-carbon, resource efficient, and inclusive economic benefits, which will facilitate sustainable development in Southern Africa.

2 Biofuels: current status and future potential

2.1 Biofuels pathways

The biomass feedstock, conversion technology, and other requirements of the biofuels value chain will determine the overall economic, social, and environmental costs and benefits. The economics of biofuels production is particularly sensitive to feedstock prices, as well as market conditions, such as the competing fossil fuel price. Several types of biomass can be used as feedstocks to produce biofuels through various conversion pathways. These feedstocks can be categorized as:

- Sugary and starchy crops, which are typically food crops. Sugary crops include sugarcane, sugar beet, and sweet sorghum; starchy crops include maize, wheat, triticale, and rye.
- Lignocellulosic biomass, which includes dedicated energy crops (grass, herbaceous plants, trees), agricultural residues (post-harvest residues that need to be collected, such as straw and corn stover; captive processing residues such as bagasse, husks, shells, and cobs), and forestry residues (branches and leaves, and residues from wood-processing activities, such as sawdust and cutter shavings).
- Oil-rich crops and oil wastes include oils from food crops, such as canola, soya, and sunflower oil, and non-food oils, such as *Jatropha*.
- Organic wastes include manures, sewage, the organic fraction of municipal solid wastes, and other food wastes.
- Algal biomass refers to aquatic plants that can be micro-algae or macro-algae, with species that can be grown in freshwater and seawater, using open ponds or photobioreactors.

There are several conversion processes that can utilize various biomass feedstocks to produce biofuels and other co-products. Conventional biofuels are those that are already commercially available, with established evidence of performance in terms of efficiency and economics. A number of other advanced and developing conversion technologies are progressing along the research and development innovation pathway, from basic and applied research and development, to demonstration and early commercialization, and finally full commercialization. The established commercial biofuels technology and those in the research and development pipeline of development include the following (IEA 2008):

1 fermentation of sugary and starch crops to produce ethanol and other alcohols such and butanol);
2 mechanical pressing and transesterification of oils (from oil-rich crops and oil waste) for the production of biodiesel;
3 mechanical pressing and hydrogenation of oils (from oil-rich crops and oil waste) to produce hydrotreated vegetable oil;
4 anaerobic digestion of various organic biodegradable wastes to produce biogas, which is then upgraded to (bio)methane;
5 pre-treatment of lignocellulosic biomass by hydrolysis to provide sugars for fermentation to produce ethanol and other alcohols;
6 pre-treatment of lignocellulosic biomass by hydrolysis to provide substrates for anaerobic digestion to produce biogas, which is upgraded to (bio)methane;
7 hydrothermal liquefaction of biomass to produce biocrude, which can be upgraded to biofuels by refining and hydrogenation;
8 pyrolysis of lignocellulosic biomass to produce pyrolysis oil and charcoal (biocrude) that can subsequently be refined to produce long-chain hydrocarbon biofuels;
9 pre-treatment of biomass by hydrolysis or aqueous phase reforming of biocrude, followed by reforming to produce hydrocarbon biofuels and hydrogen;
10 gasification of lignocellulosic biomass to produce hydrogen;
11 gasification of lignocellulosic biomass to produce methane, which can be further converted to methanol, methoxymethane or long-chain hydrocarbon synfuels;
12 gasification of lignocellulosic biomass, followed by the fermentation of syngas to produce ethanol;
13 use of algal biomass for the production of biogas, ethanol, or biodiesel through the routes described in 1–7; and
14 genetic engineering of microorganisms to produce long-chain hydrocarbon fuels.

The fermentation of sugar-rich feedstocks to produce ethanol is a well-established conversion technology. The use of starch-rich crops requires an additional step to hydrolyse starch to its sugar monosaccharide units (glucose), and this typically incurs additional energy and financial cost. Ethanol produced from fermentation is typically upgraded through purification and removal of water, and is then used instead of petrol or blended with petrol at various percentages. The sludge and DDGS (dried distillers grains with solubles) are valuable co-products of the fermentation process. Biodiesel can be produced from vegetable oils through transesterification—a chemical process that involves the addition of methanol or ethanol and an alkali such as sodium hydroxide. The seed cake left after the extraction of the oil by mechanical pressing, and the glycerol from the transesterification reaction, are valuable co-products. Biogas can be produced through the process of anaerobic digestion from a range of organic feedstocks, such as: agricultural residues, food processing wastes, manures, and dedicated energy crops (for example, grass). Biogas is a methane-rich fuel that is typically upgraded (>97 per cent methane). Once upgraded, its properties are similar to natural gas, and it can be injected into a natural gas grid or be compressed and distributed to vehicle fuelling stations.

Since crops used for ethanol (i.e. maize, sorghum, sugarcane) and biodiesel (i.e. soya, canola, sunflower) may compete with food production and affect food market prices, there is a growing interest in the use of organic wastes and non-food crops for biofuels production. Ideally, biomass feedstocks are non-food crops and do not compete for arable land and resources such as nutrients and freshwater. The wastes from the food production chain are an example of such a resource, and their use brings other development benefits in terms of avoiding pollution, but they are necessarily limited in quantity. The biomass potential from non-food crops is substantial, particularly from lignocellulose (carbohydrate polymers—cellulose, hemicellulose—and lignin), which is an essential component of plants and the only major renewable resource that can produce a significant fraction of liquid transportation fuels and renewable materials in the future, since the overall energy stored in plant biomass each year is approximately 30 times greater than the energy consumed for transportation (Hermann 2006). Lignocellulose biomass is available from agriculture and forestry residues, and grassy, herbaceous, and woody energy crops. Since lignocellulose is resistant to degradation, a key challenge is the hydrolysis pre-treatment necessary for biochemical processing via fermentation or anaerobic digestion to produce ethanol and biomethane. An alternative pre-treatment and conversion process for lignocellulose is gasification, followed by conversion to synfuels (hydrogen, methane, methanol, methoxymethane, and long-chain hydrocarbon synfuels). Other non-food biomass feedstocks for biofuels are algae that offer high levels of productivity and can grow on land unsuitable for agriculture, but require large amounts of water for cultivation. Algae can accumulate a high percentage of oils under nutrient starvation and are being explored as a source for biodiesel production. However, algal biomass may also be suitable for other biofuels conversion processes (fermentation and anaerobic digestion of wet algae and—after drying—gasification, pyrolysis, or combustion).

2.2 Biofuels conversion technology readiness

There are a range of biofuels technologies at research and development, demonstration, deployment, and established commercial stages. The *conventional* first-generation biofuels—ethanol, biodiesel, and biogas—are commercially established and produced from food and fodder crops, food wastes, and sewage. *Advanced*, second- and third-generation biofuels aim to access residuals of food crops (stems, leaves, and husks) and non-food crops (grasses, bamboo, trees, and algae), and are at various stages of development. Many of these biofuels can readily replace petrol, diesel, and natural gas, with little additional infrastructure and vehicle modification, and therefore can be blended to facilitate gradual market uptake and adoption.

The production of ethanol from the fermentation of starch/sugar crops, biogas from organic wastes, and biodiesel from oil transesterification, are established commercial technologies that are becoming price-competitive with petroleum fuels. Continued improvements in pre-treatment and hydrolysis technologies will significantly reduce capital and operating costs, as will opportunities for process integration, such as consolidated bioprocessing that enables hydrolysis and fermentation to occur simultaneously. Hydrolysis and fermentation of lignocellulosic feedstock to produce ethanol has reached an early commercial phase. DuPont, Abengoa, and Poet-DSM have been operating commercial-scale lignocellulosic ethanol plants in the United States with an installed capacity of 285 million litres per annum; GranBio and Raizen have started production in Brazil with an installed capacity of 80 million litres and 40 million litres per annum respectively; Shandong Longlife has started production in China with an installed capacity of 60 million litres per annum; and Beta Renewables has started production in Italy with an installed capacity of 50 million litres per annum. In Finland, St1 produces ethanol from waste using a number of fermentation plants situated near the sources of waste, and carries out ethanol upgrading by dehydration in a central plant. Ethanol from syngas fermentation is also an emerging option that offers increased yields, and is currently at the late demonstration to deployment phase; Ineos Bio operates a commercial demonstration plant for lignocellulosic ethanol production via syngas fermentation in the United States, with an installed capacity of 30 million litres per annum (Ineos 2013). For biomass gasification-based pathways, whole-plant energy integration is a high priority to reduce production costs, and syngas cleaning remains an important area of development, specifically high-temperature processes for the removal of tar. Biomass gasification for liquid fuels production is at an earlier stage of development; Enerkem is operating the first commercial-scale plant with an installed capacity of 28 million litres per annum of methanol, using municipal solid waste as a feedstock. For synthesis of long-chain hydrocarbon biofuels, technologies are at the demonstration and early deployment phase; Choren has shown that the simpler, more selective, and scalable catalytic processes of methanol-to-gasoline (MTG) may prove more viable than the production of diesel-like biofuels by Fischer-Tropsch (FT) synthesis, which is at the early demonstration phase (EBTP 2016). There are also research and development efforts to develop new biological routes to biofuels production through genetic engineering and synthetic biology; companies such as LS9, Joule Unlimited, and ExxonMobil are pioneering the development of biodiesel from engineered bacteria and algae (Berry 2010; ExxonMobil 2017).

The production of hydrocarbon fuels, by upgrading pyrolysis oil, is proven only at pilot or small-scale demonstration, and some of the upgrading processes are still at the proof-of-concept stage. Commercialization will require further technical innovation in fast pyrolysis and upgrading processes. However, the majority of cost reductions are expected to occur at the upgrading step, through either improved catalytic processes or by using existing oil refinery infrastructure. Ensyn produces around 12 million litres of biofuel per annum through fast pyrolysis, and is developing other fast pyrolysis plants in Brazil and Malaysia (Ensyn 2016). Other conversion routes are under development for the production of hydrocarbon fuels from biomass, and include aqueous phase reforming and direct sugar to hydrocarbon routes. These pathways will benefit from efforts to improve lignocellulosic biomass pre-treatment and hydrolysis, so that these feedstocks can be used instead of sugary and starchy food crops. The production of hydrocarbon fuels from micro-algae is at the research and development and pilot stage, with the established transesterification a more mature technology than other possible processing routes for this feedstock.

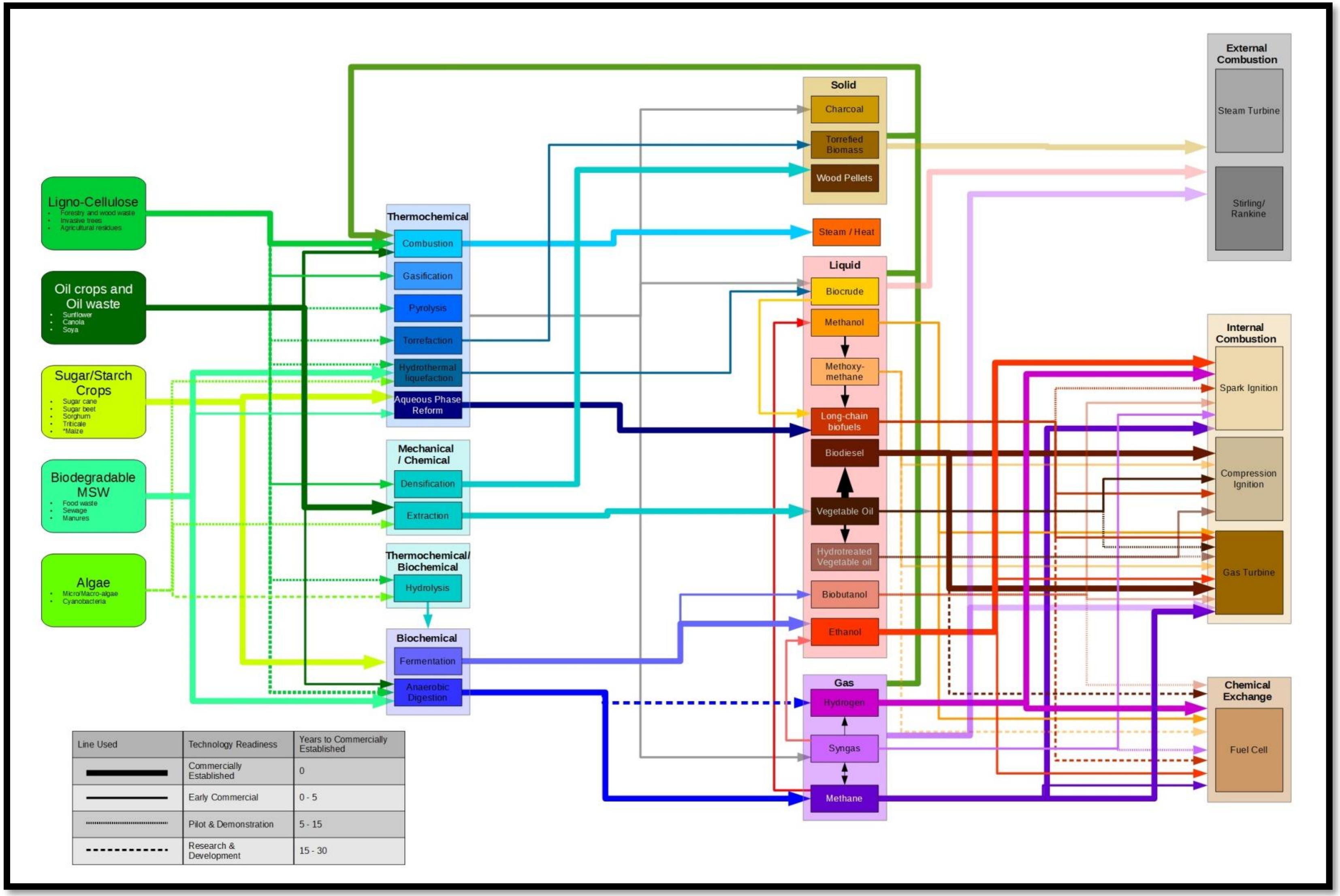
The advanced biofuels pathways can be defined by the technology readiness level (TRL) and classed at stages 1–4 (NASA 2017):

1 *Research and development* (TRL0–TRL4). Bringing new technology pathways to fruition requires a substantial amount of research, planning, and experimentation. In this phase, unproven concepts are tested, principles postulated from observations, and specific applications formulated. Subsequently, applied research is conducted at laboratory scale and the technology developed into a proof of concept via small-scale prototyping. The time to commercially establish a technology in this stage can be anything between 15 and 30 years.
2 *Pilot and demonstration* (TRL5–TRL7). Once sufficient data have been obtained from the R&D phase, larger-scale prototypes and pilot plants are developed in order to determine the scaling potential and considerations around the intended operating environment of new technologies. During this phase, prototype systems are developed, operated, and tested close to the expected performance, with the goal of creating a demonstration system. Demonstration systems are pre-commercial-scale technologies operating in the intended environment, and often used to eliminate minor operational difficulties. A successful technology in this stage can be expected to reach full commercial deployment in 5–15 years.
3 *Early commercial deployment* (TRL8–TRL9). For any technology developed at commercial scale it is necessary to create first-of-a-kind systems and flagship plants. These facilities aim to solve issues relating to manufacturing, handling, and processing feedstock, energy efficiency, and waste. Actual production at these facilities is much lower than the installed capacity, at least in part due to unforeseen technical difficulties. In most cases problems are not insurmountable and ramped-up production can be expected in the first few years of operation. This phase proves to consumers and investors the viability and commercial readiness of the proposed technology. Early adopters and market uptake play a crucial role during this phase to ensure a technology overcomes the developmental 'valley of death' before full commercial success. Once a concept reaches the early commercial phase it usually gains traction and can reach full commercial distribution in five years or less.

4 *Commercially established.* A technology is considered to be commercially established when it is readily available to consumers, and economically competitive with similar market items. Projects and technologies at this phase have overcome all major technical difficulties and are scaled-up enough to be competitive in the market and economically sustainable. Facilities and technologies that are commercially established usually operate close to maximum installed capacity. Thus, this deployment phase refers to technologies and production methods that are currently implemented and available.

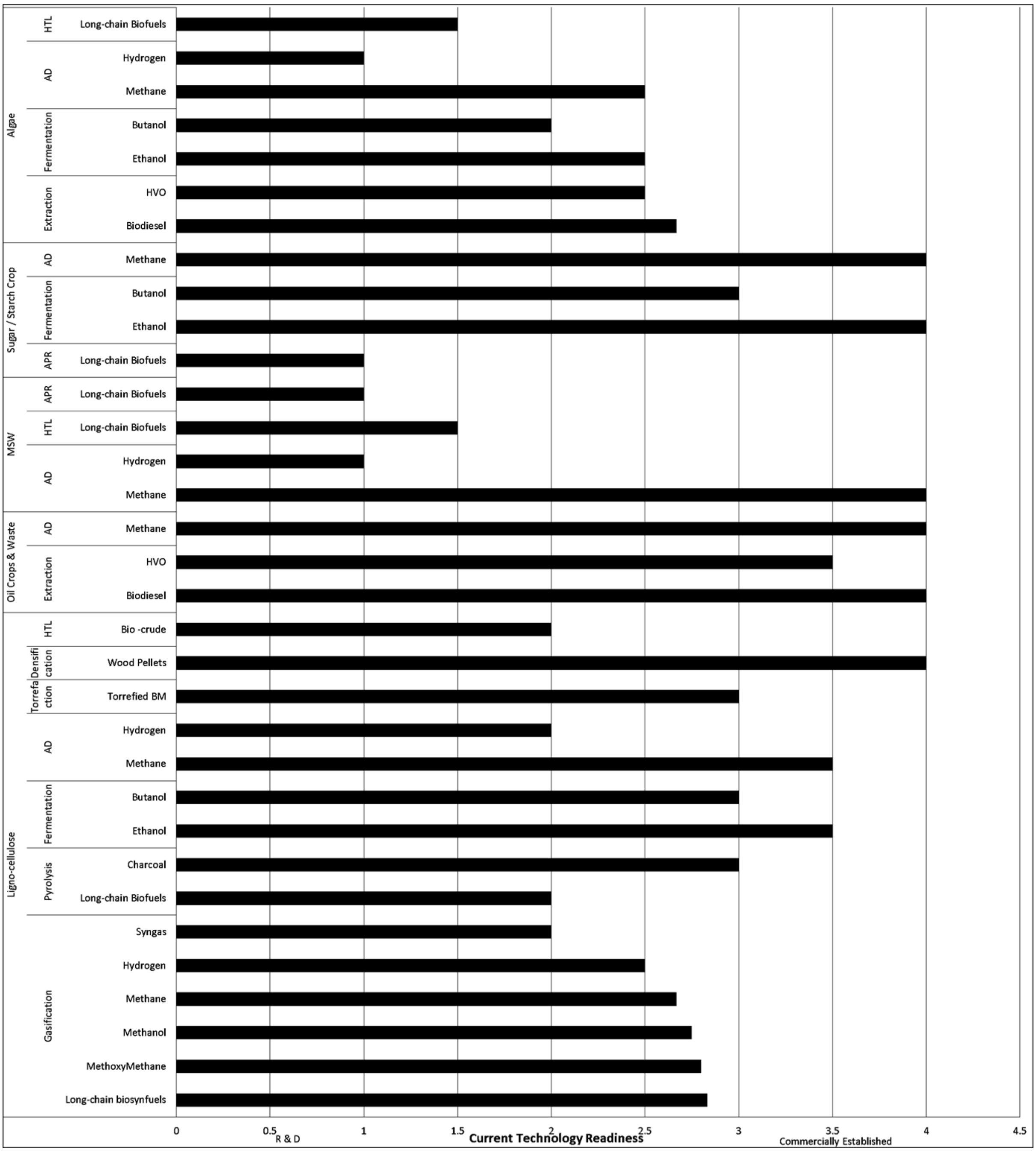
Using information from the literature, current media, and company websites, we assessed technology readiness of biofuels conversion pathways; we scored the pathways 1 to 4, according to the criteria that define technology readiness, described above. Results are shown for each conversion pathway in Figures 1 and 2. In addition, the biofuels produced can be used as fuels in various prime-movers to deliver heat, electricity, and transport. The technology readiness of the main prime-movers was similarly assessed and are summarized in Figure 3. Figure 1 also enables the combined technology readiness of conversion pathway and prime-mover to be viewed, since the width of the arrow illustrates the technology readiness, and incorporates the data from Figures 2 and 3.

Figure 1: Biofuel pathways and stage of technology readiness



Source: authors.

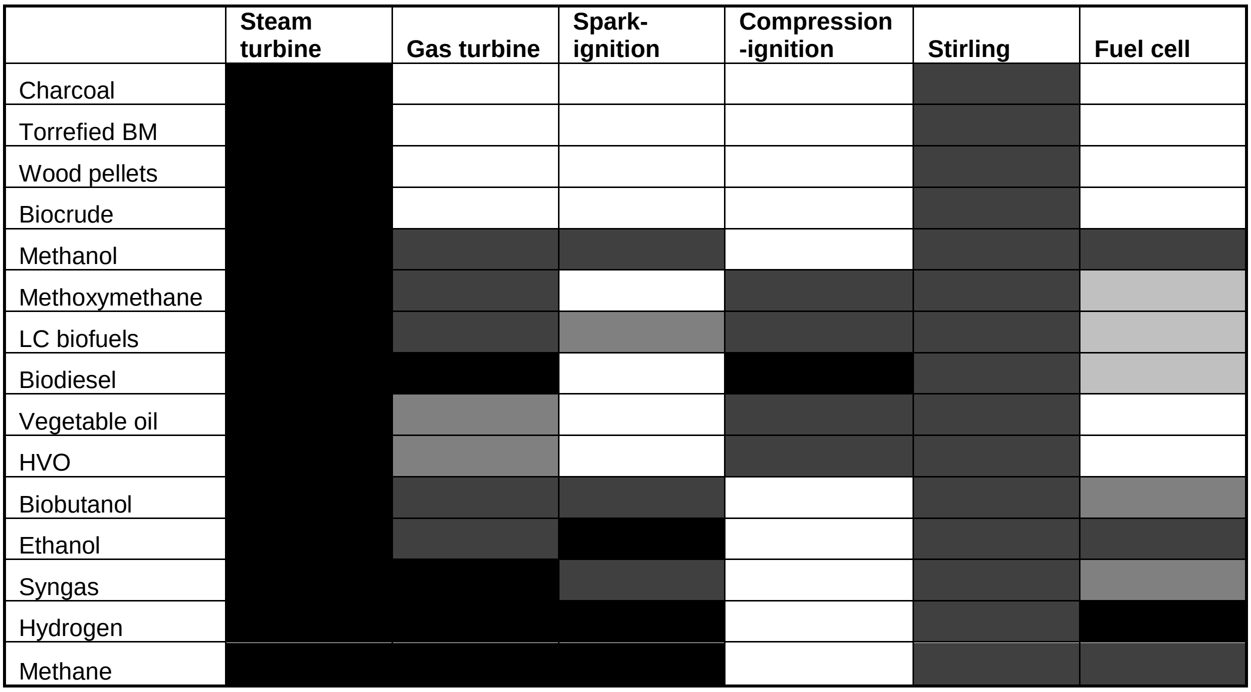
Figure 2: Biofuel feedstock, conversion process, and energy carrier readiness from pathways shown in Figure 1



Notes: AD, anaerobic digestion; APR, aqueous phase reforming; HTL, hydrothermal liquefaction; HVO, hydrogenated vegetable oil. See text for details.

Source: authors.

Figure 3: Technology readiness and/or suitability of various prime-movers for different energy carriers



	Technology readiness	TRL stage
	Unsuitable	0
	Research and development	1
	Pilot and demonstration	2
	Early commercial deployment	3
	Commercially established	4

Source: authors.

These prime-movers can have certain suitability requirements, and encompass steam turbines, gas turbines, spark-ignition engines and compression-ignition combustion engines, fuel cells, and Stirling/Organic Rankine Cycle engines. The established, commercialized prime-movers for transportation are combustion engines (spark- and compression-ignition), and early commercial battery-electric vehicles. Fuel cells are at various stages of demonstration and early commercial development. It is likely that ethanol and biodiesel will be able to readily displace petrol and biodiesel in existing transportation combustion engines, with biofuels blending providing and enabling the uptake mechanism. However, given the rapid development of the electric vehicle market, it is possible that electric vehicles may leapfrog internal combustion engines using biofuels as a future transport fuel. However, this relies on adequate grid infrastructure (electrification) and the use of renewable energy in the electricity supply mix, including electricity generated from biomass, in order to achieve environmental benefits, such as greenhouse gas emission savings (IEA 2011a; IRENA 2013).

In addition to technology readiness, there are various other factors that will determine the pace and direction of biofuels development. This includes the regional biomass supply, vehicle fuel demand, market instruments, and fiscal mechanisms. The rate of adoption and pace of biofuel developments will largely be determined by policy and country-specific mandates to reduce carbon emissions. The EU Energy Technology Perspectives Blue Map scenario sets targets to reduce global energy-related greenhouse gas emissions. The percentage of biofuels in the transport fuel mix should increase from 2 per cent currently to reach 27 per cent by 2050, thereby avoiding 2.1 Gt of CO_2 emissions per year (IRENA 2016a). This level of adoption will require considerable technology developments so that conventional ethanol and biodiesel production are gradually superseded by advanced cellulosic and advanced biodiesel, respectively. In addition, although residues and wastes can supply some of the biomass feedstock required for biofuels production, the land for biofuels use will likely triple between 2010 and 2050, to reach about 110 Mha (IRENA 2016a).

The extent of biofuels market penetration will depend on competing alternative fuels and the additional infrastructure and market requirements that facilitate market uptake and adoption. In the EU Blue Map scenario for transport, the carbon-reduction targets are also partly achieved by an increase in electric vehicles to reach 13 per cent in 2050, with the electricity substantially supplied from low-carbon, renewable sources. Several other countries have made similar commitments to transition to electric vehicles. The Electric Vehicle Initiative (EVI), a multi-government policy forum dedicated to accelerating electric vehicle development worldwide, reports a rapid exponential growth in electric vehicles, with China and India leading the adoption—particularly e-bikes and scooters (IEA 2011b, 2016). Interestingly, South Africa is the only African nation to form part of the EVI.

Natural gas vehicles are also alternative transport fuels that will compete with biofuels in current and future transport fuel markets. Natural gas currently powers approximately 2 per cent of the global vehicle fleet, and has seen an annual growth rate of 25 per cent between 2001 and 2010. Several countries in Africa have natural gas fields in their territories (South Africa, Namibia Angola, Mozambique, and Tanzania), and could supply fuel for the natural gas vehicles fleet, as well as providing electricity and heat to households and industry. The use of natural gas for transport is developing in Johannesburg, South Africa, where there is an established gas and natural gas vehicle refuelling station (Kilian 2016). Similarly, hydrogen is an alternative transport fuel that can power vehicles using internal combustion engines and fuel cells and is at demonstration and deployment stage, with Toyota, Hyundai, and Honda offering vehicles in selected markets. Although both hydrogen and natural gas are clean-burning, they can only offer low-carbon benefits when renewable energy resources are used for their production; such as methane from anaerobic digestion or gasification of biomass, and hydrogen from electrolysis of water using wind or solar power.

3 Performance criteria and constraints for biofuels development

3.1 Biofuels energy yield, conversion efficiency, and net energy balance

The conversion efficiency of biofuels is typically expressed as the energy yield of biofuel per unit biomass feedstock input. However, biomass productivity varies widely with locality due to climate and soil conditions, so that the biofuel yields per unit land area is a preferred measure of biofuels conversion efficiency. An added consideration is that some technologies produce other valuable co-products that need to be accounted for. Good biomass productivity with optimal attainable yields per hectare requires the use of land and climatic conditions suitable for biomass growth, water and soil nutrients, as well as plant species suited to the specific agroecological zone and local climatic conditions. In general, biofuels conversion efficiency is predicted to increase by 30–40 per cent until 2050 as a result of improvements in biomass yields and efficiency of biofuels conversion technology (Table 1). From this comparison, it can be seen that ethanol production achieves a greater yield per hectare than biodiesel. In addition, the ethanol yields per hectare from sugarcane and sugar beet are greater than other feedstocks such as maize, barley, and wheat. In Brazil, the ability to switch mills to produce either biofuel or sugar is a way of adjusting to fluctuation in global sugar prices and buffers the sugar industry from oversupply of sugar.

Table 1: Yields of biofuels and co-products per land area

Feedstock/biofuel	Biomass yield (t/ha), as received	Biofuel energy yield (GJ/ha)		Co-products (kg/ha crop)
		2010	2050	
Sugar beet ethanol	46	83.16	109.89	1050 beet pulp
Maize ethanol	7.15	53.46	71.28	810 DDGS
Sugarcane ethanol	67.1	115.82	142.55	14,624 bagasse
Cellulosic ethanol[a]	15	65.34	109.89	1320 lignin
Rapeseed diesel	2.5	57.5	65.21	167 glycerine 1,000 presscake
Soy seed diesel	2.55	23.0	27.95	67 glycerine 533 bean meal
Palmseed diesel	19.2	122.67	149.04	356 glycerine 889 bunches
Biomass-to-liquid diesel[a]	15	160.42	269.09	Low-temperature heat Pure CO_2
Hydrotreated vegetable oil diesel[b]	2	76.67	130.33	222 glycerine
Algae diesel	60	N/A	N/A	Several

Notes: The assumed biomass yield was used to estimate the energy yield in GJ/ha. Energy density used for conversion of ethanol = 19.8 MJ/L and biodiesel = 34.5 MJ/L.

[a] The average yield of woody crops from short rotation coppice (SRC) = 15 t/ha.

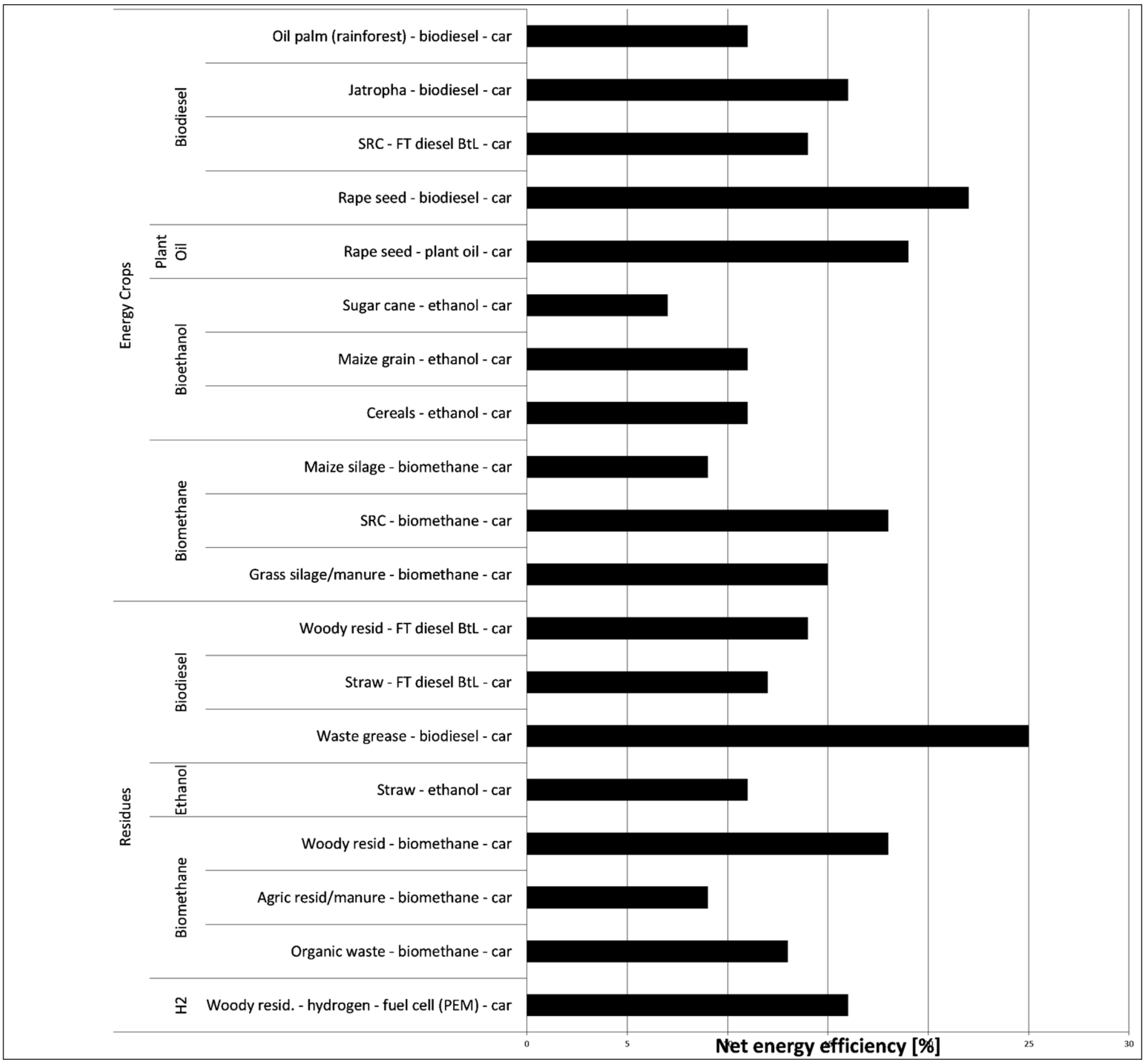
[b] From *Jatropha*.

Source: adapted from IRENA 2013.

The biofuel energy yield is determined by the yield of biomass feedstock and the biofuels conversion efficiency (Table 1), but there are other energy requirements in the biofuels value chain that will affect the overall or net energy efficiency. This includes energy required for: the production of the seeds, pesticides, and fertilizers; for irrigation; cultivation of the land; transportation to the biofuels conversion facility; as well as energy required to distribute the biofuels to market and energy losses in end-use. The net energy of biofuels is calculated as the ratio between the energy delivered by a particular fuel to society and the energy invested in the capture and delivery of this energy. Life-cycle assessment (LCA) (ISO 2006) provides a useful framework and tools to assess the net energy of various biofuels from biomass to wheel, and is expressed as life-cycle energy efficiency (see Figure 4). Due to the energy requirements to distil ethanol fuels and the lower efficiency of spark-ignition internal combustion engines, the use of biomethane and biodiesel for transport offers greater net energy efficiency. Furthermore, the use of waste biomass or the whole plant from energy crops, and the efficiency of the prime-mover (internal combustion engine is typically 25–30 per cent, while an electric motor is 80–90 per cent) are important determinants of the overall or net energy efficiency.

It is important to note that there is considerable inconsistency in the literature when calculating the net energy efficiency due to the use of different indicators, system boundaries, and assumptions applied (Davis et al. 2009). For example, net energy balance, net energy balance ratio, fossil energy ratio, energy return on investment, net energy value, and life-cycle energy efficiency have been used to describe the energy efficiency of biofuels pathways. Inconsistency in defining these terms and the use of indicators that only account for fossil energy inputs or do not account for energy content of biomass, will overestimate the life-cycle energy efficiency. The application of different system boundaries also strongly influences life-cycle energy efficiency estimates (NREL 1998), since the boundary may be defined from field-to-wheel, biomass-to-wheel, fuel-to-wheel, or field-to-fuel. Furthermore, varied and often contradictory results can be obtained by allocating resource and energy flows between biofuels and co-products according to either market price, weight, energy content, or the avoided processes from product substitution (Malça and Freire 2006). Using the life-cycle energy efficiency from biomass to wheel ensures that the most energy-efficient biofuels are those that perform well in terms of high biomass yields, high biofuels conversion efficiency, and low energy input requirements.

Figure 4: Net energy efficiency of biofuels (biomass-to-wheel) from feedstock production to end-use in transportation



Notes: Life-cycle energy efficiency = (energy output / energy input) × 100.

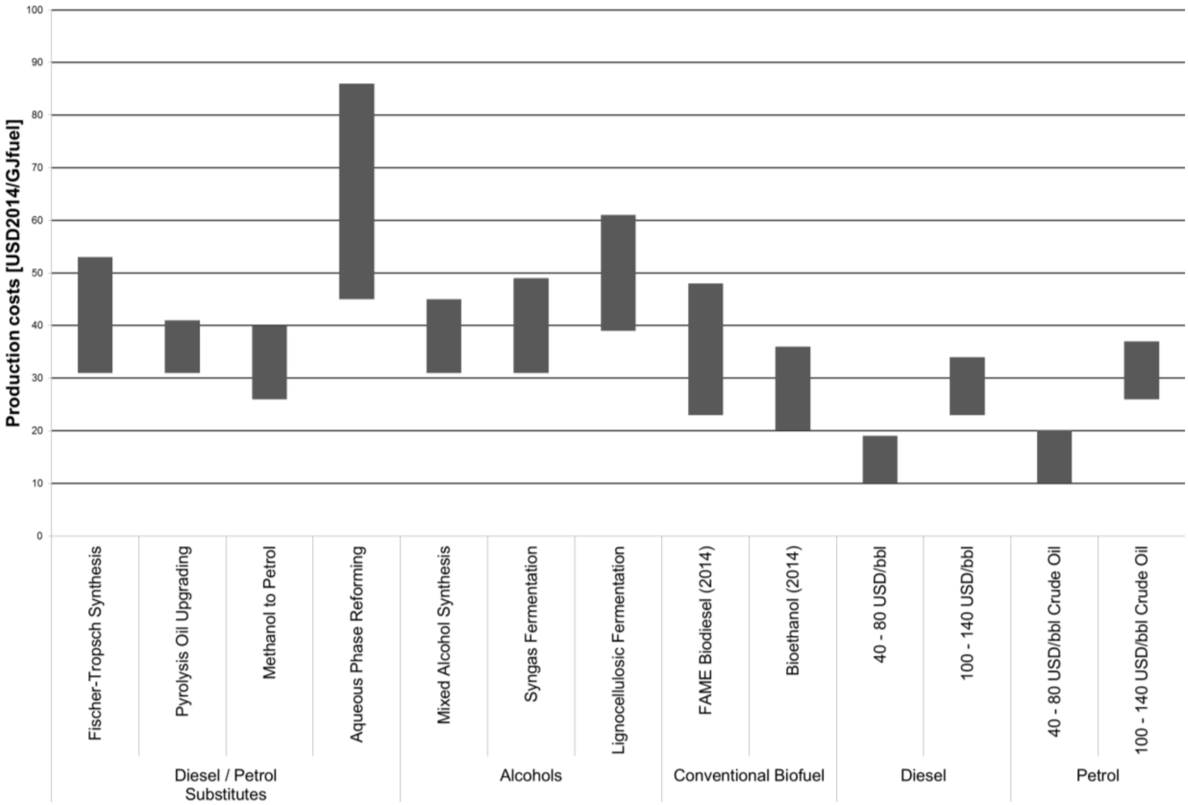
Source: adapted from Schubert et al. (2008).

3.2 Cost competitiveness of biofuels compared to fossil fuels

In general, biofuels are not yet economically competitive with conventional fuels (i.e. petrol and diesel); prolonged low crude oil prices will limit the market potential of biofuels. A possible exception is Brazilian sugarcane ethanol that can now produce ethanol at US$20/GJ (Figure 5).

However, all major biofuel initiatives were only possible through extensive state intervention and the effective subsidizing of the sector and blending mandates. Private-sector investment in the sector is currently unlikely unless there is a consistent increase in oil prices and/or substantive government incentives to make this happen. Currently, advanced and second-generation biofuels are significantly more expensive than conventional biofuels. In all cases, the feedstock is a significant cost component, as it may account for 60–90 per cent of the overall cost of a biofuels production facility (IRENA 2016b). An important consideration is that the sale of co-products (e.g., glycerine, bagasse, lignin, seedcake, heat, and power) from biofuels production can reduce the biofuel costs by 15–20 per cent. The current and projected costs are shown in Figure 5 (Worldwatch Institute 2006).

Figure 5: Biofuel production cost, compared to diesel and petrol equivalents



Notes: assumes oil price of either 40–80 US$/bbl or 100–140 US$/bbl). USD/bbl = US$ per barrel oil).

Source: adapted from IRENA 2016b.

Biofuel production costs often have considerable range due to the high biomass cost component. Furthermore, many of the advanced biofuels technologies that are early in the technology readiness stage of development have large uncertainties in costs. As these technologies mature through further research and development, uncertainties in production costs and technology risk will be diminished. Most biofuel production costs have a variance of 11–26 per cent (Figure 5), which is important to be aware of when considering technology maturity and investment risk.

A common feature of all biofuel conversion technologies in terms of reaching the market is the ability to generate valuable co-products that can improve the overall economics and feasibility of the conversion technology. This approach is being developed further through the biorefinery concept, where renewable biomass sources are used for the production of biofuels and a range of other co-products. The economic competitiveness of this biorefinery approach is due to the production of both high-value, low-volume co-products (such as seedcake for animal feed), as well as comparatively low-value, high-volume co-products, such as biofuels. At an oil price of less than US$80/bbl, advanced biofuels are very unlikely to compete directly with gasoline and diesel. However, at oil prices above US$100/bbl, most advanced biofuels pathways may be able to compete directly with gasoline and diesel by 2030–45.

The optimum plant size of biofuels conversion is significantly influenced by the scaling exponent for biofuels production. Historical data from the chemical industry indicates that the scaling exponent for industrial production is on average 0.6; commonly known as the six-tenths rule of thumb (Leboreiro and Hilaly 2011). Although higher scaling exponents for biofuel plants have been reported (Fisher Jr et al. 1986; Nguyen and Prince 1995; Searcy and Flynn 2009), studies indicate that most range between 0.5 and 0.8 (Wright and Brown 2007). In addition to the scale of biofuels production, the optimum plant size at a given locality is also influenced by the feedstock transportation costs, which necessarily increase with plant scale (McIlveen-Wright et al. 2001; Overend 1982; Perlack and Turhollow 2003). The optimal total unit cost of biofuel production is therefore a solution that 'trades off' the economies of scale that favour larger biofuel conversion plants with the increasing costs of transport and storage required for feedstock. The optimum scale is the ratio of scale factors (exponents) of the transport and production costs. For example, a hypothetical biofuels with capacity exponent for production costs, $n = 0.6$, and capacity exponent for transport, $m = 1.6$. If $M = m - 1$ and $N = 1 - n$, then the optimum scale, S, is defined as: $N / M = 0.67$, and indicates that the optimal scale is 67 per cent of the overall costs.

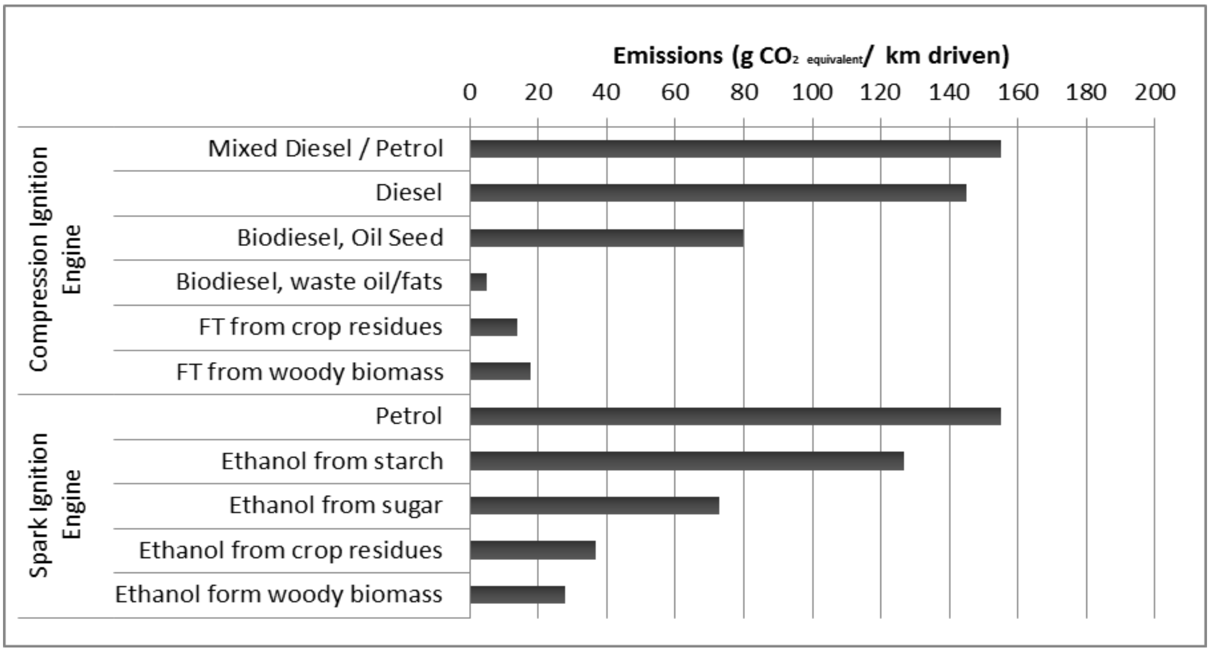
Both ethanol and biodiesel can be produced at almost any scale, but it appears that there are better economies of scale for ethanol production. As an example, in Australia cane sugar and cane plus sweet sorghum ethanol plants have optimum capacities around 245 million litres and 175 million litres per annum, respectively (Nguyen and Prince 1995). The production of biodiesel is generally less sensitive to transportation and has fewer economies of scale (scale factor), so the optimal plant size is about 23 million litres per annum (Nolte 2007). This is partly related to the ability to store feedstock; where feedstock is a difficult crop to transport with short shelf-life after harvest (such as sugarcane), there is minimal opportunity to optimize the value chain logistics and a greater scale in production near the facility is required to ensure viability. The consequence of this is that ethanol plants typically require substantive financial investment for their large scale, as well as close synchronization between feedstock production, ethanol production, and the market.

The cost competitiveness of biofuels will also be highly dependent on the ease of market uptake and additional infrastructure and vehicle modifications needed. Anhydrous ethanol is ethanol of less than 1 per cent water, and is typically used in blending with petroleum to create E10 blends (10 per cent anhydrous ethanol to 90 per cent petroleum), prevalent in the United States, and E25 (25 per cent anhydrous ethanol to 75 per cent petroleum), prevalent in Brazil. This anhydrous ethanol production requires additional investment (beyond simple distillation), as an additional drying process is required that has economies of scale and is also energy intensive. Hydrous ethanol can be achieved through distillation alone and can contain up to 4.9 per cent water by volume, but can be used without blending in special flexible-fuel vehicles, as is often the case in Brazil, or blended at 15 per cent with petrol, as has been piloted in the Netherlands (Gupta et al. 2011). Biodiesel, if of good quality, can effectively be blended at any percentage from 0 to 100 per cent with conventional diesel. The only two key problems that might be encountered are that it has a cleaning property and may dislodge dirt from the fuel tank, necessitating more regular filter changes when first used, and it can destroy rubber compounds in gaskets, which is of concern in older vehicles. Blending ethanol with petroleum changes the octane numbers and therefore requires careful consideration. Unless dual-fuel cars are involved there is a limit to how much ethanol can be blended with conventional gasoline for use in petroleum engines. In the United States all cars can use E10, but only post-2001 cars are approved by the Environmental Protection Agency (EPA) to use E15.

3.3 Greenhouse gas emissions and air pollutants

A significant driver for the adoption of biofuels is the reduction of greenhouse gas emissions and other pollutants. In general, biofuels reduce both local pollution (particulate emissions, nitrous oxides) and global carbon dioxide levels, compared to reference fossil fuels. The greenhouse gas emissions from biofuels have been extensively published and most studies reveal significant carbon savings compared to petroleum fuels (Figure 6).

Figure 6: Greenhouse gas emissions of biofuels from lignocellulose feedstocks and energy crops, compared to reference fossil fuels (petrol and diesel)

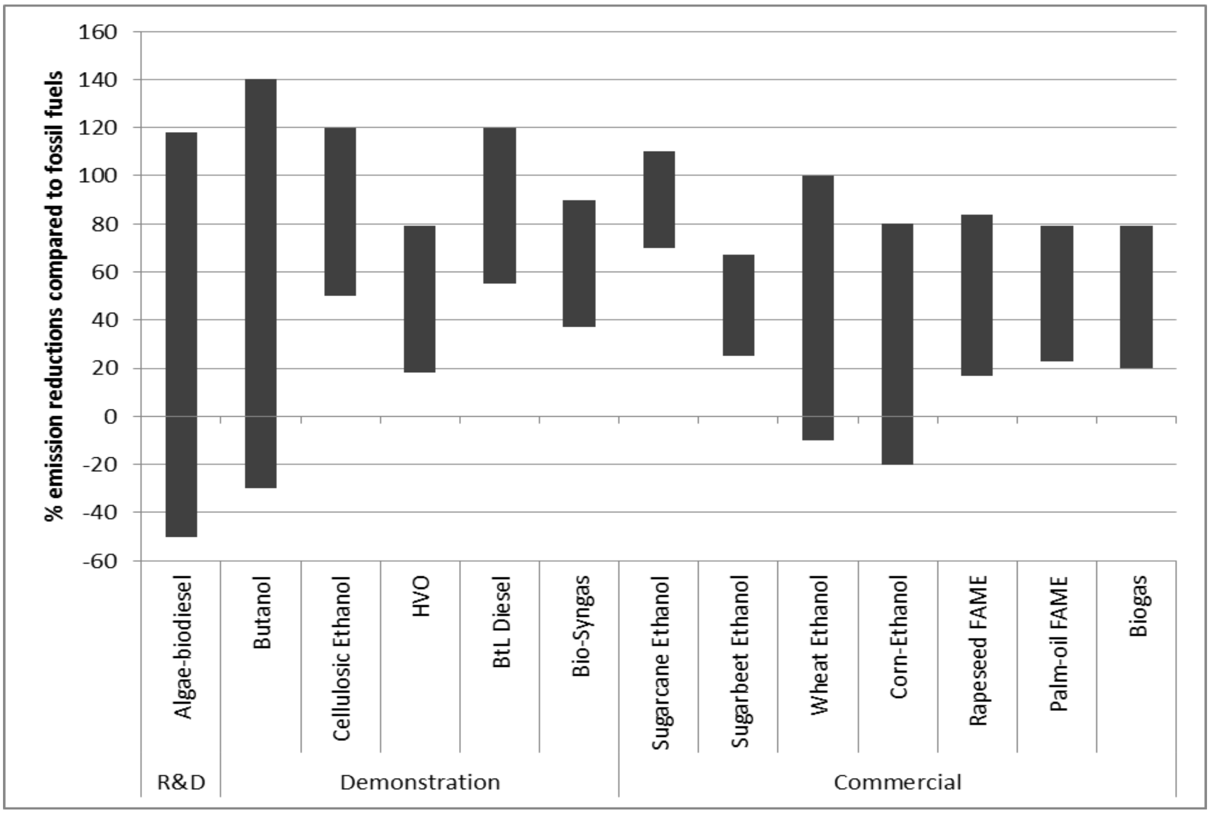


Source: adapted from IEA 2008.

The use of sugary biomass (sugarcane and sweet sorghum) for ethanol production using first-generation technology has greater carbon savings compared to ethanol produced from starchy sources. The use of second-generation and advanced technologies that utilize lignocellulosic biomass offer even better carbon emission reductions. However, these technologies are not yet established at commercial scale, nor are the benefits fully verified. Using wastes and biomass residues (i.e. whey for ethanol and recycled plant oil for biodiesel) offers the lowest carbon emissions, since there are no emissions for cultivation of the resource. These resources are the most favourable in terms of greenhouse gas mitigation and reducing the emission of pollutants, as well as reduced costs from avoiding the disposal of these wastes (Transport Research Centre 2008).

However, several studies on the carbon emission reductions of biofuels have reported a wide range of values for a given biofuel pathway, and this has caused considerable debate. The differences are due to various factors, such as the locality of the biofuels development (biomass productivity and transportation requirements), the conversion technology, and the methodology used (especially the boundary and assumptions in accounting for biofuels and co-products). In addition, the loss of natural areas and fuel-intensive farming practices for agriculture are already responsible for a significant portion of global anthropogenic greenhouse gas emissions, and there are concerns that biofuels will result in further expansion and additional impacts. The carbon emissions from land-use change are due to the large carbon debt incurred from agricultural expansion to grow energy crops, and can completely negate the carbon savings from using biofuel (Schubert et al. 2008). Both direct and indirect land-use changes can occur and should be accounted for. However, the measurement and accounting of these land-use changes are problematic and carry considerable uncertainty.

Figure 7: Meta-analysis of greenhouse gas emission reductions of various biofuels, compared to reference fossil fuels (diesel and petrol)



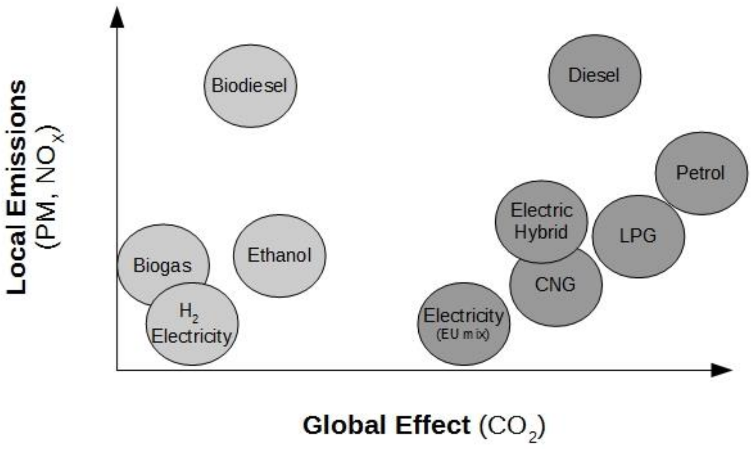
Notes: The assessments exclude indirect land-use change. Emission savings of more than 100 per cent are possible through use of co-products. BtL = biomass-to-liquid; FAME = fatty acid methyl esthers; HVO = hydrotreated vegetable oil.

Source: results are from numerous LCA studies; the figure is adapted from IEA 2011a.

From a meta-analysis of carbon emissions from numerous LCA studies, biofuels can clearly deliver carbon savings compared to reference fossil fuels. However, actual carbon savings are context-specific and, in some cases, carbon emissions may be greater than reference fossil fuels (negative values in Figure 7). Also, in many studies the land-use change impacts are not included in the analysis. In the Southern African context the land-use change impact is dependent on the vegetation status prior to the project implementation, and may be trivial in already degraded landscapes, but high if virgin forest is cleared (Romeu-Dalmau et al. 2016). Certainty of achieving carbon emission reductions is therefore an important criterion to consider when comparing the maturity of various technologies. There is a large degree of uncertainty in achieving the expected carbon emission reductions of many advanced biofuels that are at early stages of development (Figure 7). For example, the reported variance in carbon emission reductions is 18 per cent for conventional technology to produce sugarcane ethanol and 40 per cent for rapeseed biodiesel, while the advanced cellulosic ethanol is 29 per cent, and advanced algal biodiesel technology is 87 per cent. Interestingly, ethanol production using starchy crops such as wheat or corn has greater uncertainty in achieving carbon emission reductions compared to ethanol obtained from sugarcane or sugar beet. The certainty of achieving carbon emission reduction benefits will increasingly affect investment decisions, given the growing carbon markets and imperatives to reduce greenhouse gas emissions in order to mitigate global climate change.

There are a range of other environmental impacts to consider in addition to carbon emissions. A notable impact of high mitigation priority is the air pollution of biofuels due to sooty particulate matter and oxides of nitrogen and sulphur. Figure 8 is a diagrammatic representation of how biofuels perform in terms of global effect (greenhouse gas emissions) and local emissions (air pollutants) compared to fossil fuel counterparts of petrol, diesel, and natural gas. Further, biofuels may well have profound negative impacts on biodiversity (Blanchard et al. 2011; von Maltitz et al. 2010).

Figure 8: Diagrammatic representation of the performance of biofuels compared to petroleum fuels in terms of global effect (greenhouse gas emissions) and local emissions (air pollutants)



Source: adapted from Baltic Biogas Bus 2009.

Other environmental impacts to consider include: water consumption, water acidification and eutrophication, biodiversity loss, soil degradation, and pesticide impacts (Frischnecht et al. 2006; Gasparatos et al. 2012). Agriculture and farming practices are already using approximately 70 per cent of water from surface rivers and streams (IPCC 1997), and contribute to water pollution from excess nutrients, pesticides, and herbicides (Gerbens-Leens et al. 2009; Gopalakrishnan et al. 2009). Currently it is estimated that approximately 1,388 to 19,924 litres of water are needed per litre of biofuel produced (Gerbens-Leens et al. 2009; World Energy Outlook 2012), and if the world's agricultural land and freshwater currently used for growing biofuels (*c.*4 per cent) was used for food production, it could feed one-third of the malnourished people in the world (Rulli et al. 2016). The additional water demands for widespread biofuels production in Southern Africa are unlikely, since most of Southern Africa—with the exception of Angola, Mozambique, and parts of Zambia—are semi-arid and water scarce. As with all land transformation activities, the effects on biodiversity and ecosystem services of producing feedstocks for biofuel are highly variable and context-specific, and are dependent upon the particular biofuel technology, production and distribution system, policies, stakeholders and their values, and the baseline ecosystem conditions or state (Efroymson et al. 2012). Where feedstocks for biofuels are planted in pristine landscapes, significant biodiversity losses can be expected (Harrison and Berenbaum 2013; Leal et al. 2013; Phalan et al. 2013). Further, many dedicated energy crops are chosen for their high productivity and vigorous growth; many are non-native to the region and could become 'problem plants' if they are invasive, with the ability to thrive and spread aggressively outside the planted area into natural vegetation (Blanchard et al. 2011).

There are also complex land tenure structures in Southern Africa, and the lack of infrastructure in rural areas presents additional challenges to the expansion of biofuels production. Biofuel developments could threaten the livelihoods of many of Africa's rural poor through the displacement of indigent people from communal lands—'land grabs' (Gasparatos et al. 2012; Kline et al. 2009; Robertson et al. 2008; Scharleman and Laurence 2008).

Biofuel technology will therefore need to be tailored to local needs, priorities, and development agendas, and be well planned to ensure the improved renewable energy supply and energy security are more integrated with sustainable agricultural systems based on energy efficiency and improved natural resource management (de Vries et al. 2010; IAASTD 2009). The hitherto assessment of biofuels obstacles and constraints can be used to develop recommendations for more sustainable biofuels, as follows:

- Evaluate the entire life-cycle of biofuels—feedstock production, biofuels conversion, end-use, and waste disposal—to calculate the biomass-to-wheel greenhouse gas emissions and other environmental impacts in order to determine the ecological footprint and benefits of biofuels compared to petroleum fuels.
- Select high-yielding biomass species suited to the land capability and the agroecological zone.
- Choose technologies with high conversion efficiencies in order to minimize land area needed to produce biofuels, and to minimize waste produced.
- Encourage restoration or reclamation of degraded areas for biofuel cultivation wherever appropriate in order to limit agricultural expansion into natural areas (additional land-use change).
- Promote the use of energy crops that can be grown with low fertilizer, pesticide, and energy inputs in most settings.
- Promote the use of native and perennial species and apply a precautionary principle to species selection in order to avoid exotics that can become invasive problem plants.
- Promote polyculture, inter-cropping, and crop rotation that can help to increase on-farm biodiversity and improve the management of biomass resources for both food and biofuels.
- Employ agricultural cultivation techniques and practices (e.g. conservation tillage) that conserve soil carbon and nutrients, reduce water requirements, and increase on-farm biodiversity.
- Ensure that biofuels technology and value chains are tailored to local conditions and community needs through more participatory and inclusive development processes.
- Develop more equitable biofuels business models that can deliver notable development opportunities to poor, smallholder producers.
- Use biofuels certification schemes to set norms and standards or 'best practice' to help ensure biofuels benefit 'people, profit, and the planet'. Examples include the Roundtable on Sustainable Palm Oil, the Roundtable on Responsible Soy, Bonsucro, and the Forestry Stewardship Council, who certify palm oil, soy, sugarcane and timber/wood, respectively, and the Roundtable on Sustainable Biofuels, and International Sustainability and Carbon Certification, who certify biofuels and biomaterials.

4 Conclusions

Biofuels can help mitigate climate change by reducing carbon emissions while also reducing local air pollution, improving energy security, and offering new opportunities for rural development. However, the benefits of biofuels depend on the feedstock, conversion pathway, and local context. The various biofuels conversion technologies are at different stages of R&D and this can define their technology readiness and maturity. The currently established commercial biofuels use food crops, manure, crop residues, and food wastes to produce ethanol, biodiesel, and biomethane, and generally provide 20–80 per cent savings on carbon emissions compared to the petroleum fuels they replace (petrol, diesel, and natural gas). Currently, first-generation technologies are mature and in wide-scale operation in many regions. Biofuel based on sugarcane ethanol is well-established in Brazil, which has many similar social and environmental conditions to Southern Africa and can help guide development. First-generation biofuel options based on oil crops are also possible, but per-hectare energy returns are far lower than the ethanol options. In the medium to long term it is foreseen that technologies that can use the non-food components of biomass are likely to dominate; these technologies can give better yields of biofuel and out-perform first-generation technologies on most indicators. These technologies are still in development or piloting paths, and currently are not cost competitive with either first-generation technologies or fossil fuel prices.

The use of wastes and biomass residues offers the greatest carbon reductions, since there are no emissions for cultivation of the resource and reduced emissions and costs from avoiding the disposal of these wastes. However, resources are limited and may compete directly with food-supply systems. In contrast, the advanced biofuels technology that uses non-food crops and residues, coupled with efficient conversion technology, will enable the lignocellulosic component of biomass to be used with various suitable technologies at various stages of research and development. Hydrolytic pre-treatment of crop residues, such as straw, for ethanol fermentation is at an early commercial stage, as is the pre-treatment of organic waste for enhanced anaerobic digestion. Gasification of lignocellulosic biomass and either ethanol fermentation or synfuel production (methane, methanol, methoxymethane, and long-chain hydrocarbons via FT and MTG synthesis) is currently at the pilot and demonstration stage. Pyrolysis and upgrading of biocrude (oils and char) is at the pilot and demonstration stage, while aqueous phase reforming and the use of algae and engineered microorganisms are at research to early pilot and demonstration stages. The use of advanced biofuels conversion pathways that utilize lignocellulose offer even greater carbon savings, but since they are not yet established the benefits are more uncertain.

From an economic perspective, Southern Africa (SADC) cooperation for regional biofuels development is appropriate since South Africa has a high transport fuels demand, while many of its neighbours have greater potential biomass productivity. Currently, most biofuels are more expensive than their petroleum counterparts and the extent of biofuels market penetration will be influenced by mandates (blending targets) and subsidies (green premium). The economics of biofuels production favours large scales, but is highly dependent on feedstock costs that typically account for 40–60 per cent of total costs. The market uptake will also be governed by competing alternative fuels and technologies, such as natural gas, hydrogen and battery-electric vehicles, although these options may require additional distribution infrastructures and will only deliver carbon benefits if the electricity mix is substantially powered by renewables. Given the rapid global development of hydrogen fuel cell and electric vehicles, it is likely that South Africa will meet its 2–10 per cent biofuels blending mandate in the short term (5–20 years), while moving to adopt electric vehicles at scale in the longer term (20–40 years). Other SADC countries will likely follow suit in electric vehicle adoption, but with considerable delay since the electricity grid is less established.

Developing biofuels will require a careful assessment and certification of the supply chain and biofuels life-cycle to avoid unintended consequences. If biofuels development clears natural areas, and biofuels are produced from low-yielding crops, grown with heavy inputs of water, fertilizers, and energy, and/or processed into biofuel using fossil energy, they could threaten food security and generate as much (or more) carbon emissions than do petroleum fuels. However, if developed appropriately, biofuels offer an opportunity for the production of renewable energy and a reduction in carbon emissions, together with the development of more integrated and sustainable agricultural systems and improved natural resource management.

Since there is a limited amount of fertile land available, there is global concern that the use of land for biofuels can result in competition with food production and other valuable biomass products (fodder, timber, fine chemical, fibre, and textile production), and thereby threaten the livelihoods of many of Africa's rural poor, and displace indigent people from communal lands. Biofuels development therefore requires a balancing of priorities since fertile land, water, and other inputs that are used to grow feedstock for biofuels could also have been used to grow food. The complex land tenure systems and the general lack of infrastructure in rural areas are additional barriers to the development of biofuels in many African countries. However, if developed appropriately, bioenergy projects offer an opportunity for the production of renewable energy and the displacement of fossil fuels as energy sources, and also the development of more integrated and sustainable agricultural systems with improved natural resource management.

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