

# Green Diesel, Renewable Energy and Waste Cooking Oil: The Potential for Synergy

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## Abstract

Excess capacity at Eskom is currently in the region of 5 GW, resulting in the stonewalling of cheaper solar PV generation contracts. The slow take-off of the 2% national biofuel blending policy can possibly result in 970 million litres per annum of bio-sourced diesel being stranded as waste yellow/brown grease. At the same time, there is a petrol and diesel production shortfall due to capacity constraints in the face of a 3% annual growth in consumption. An integrated framework that couples the underpinning technology for these diverse challenges could hold the key to unlocking sustainable growth in all three sectors. A biodistillate plant powered primarily by renewable energy with yellow/brown grease as feedstock that produces sulphur free, higher heating value hydrogenation derived renewable diesel (HDRD), is hereby proposed

**Keywords:** Excess capacity, Capacity constrain, Biodistillate, Yellow/brown grease.

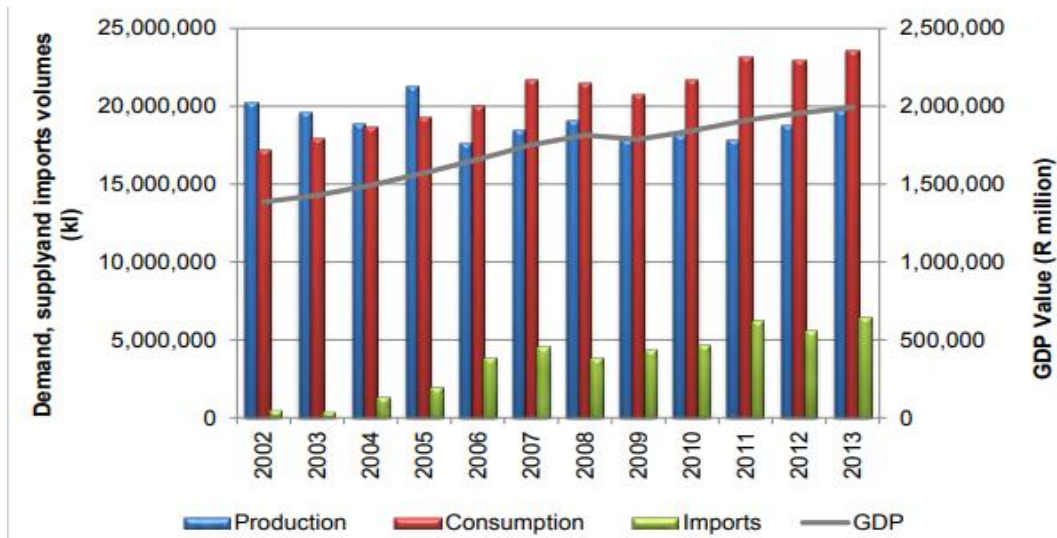
## INTRODUCTION

A raft of progressive legislation and well-crafted policy drivers have greatly advanced the growth of the renewable energy (RE) sector in South Africa in the last decade, particularly in the electricity sub-sector. This, along with a bounteous supply of non-depletable renewable sources such as wind and solar, has led to rapid growth of capacity. By the end of June 2015, 37 independent power producers had already started commercial operation, adding 1 860 MW capacity to the power system (i.e. 4% of the total installed capacity) within 2.5 years [1, 2]. It is projected that by 2030, 17.8 GW of the expected total

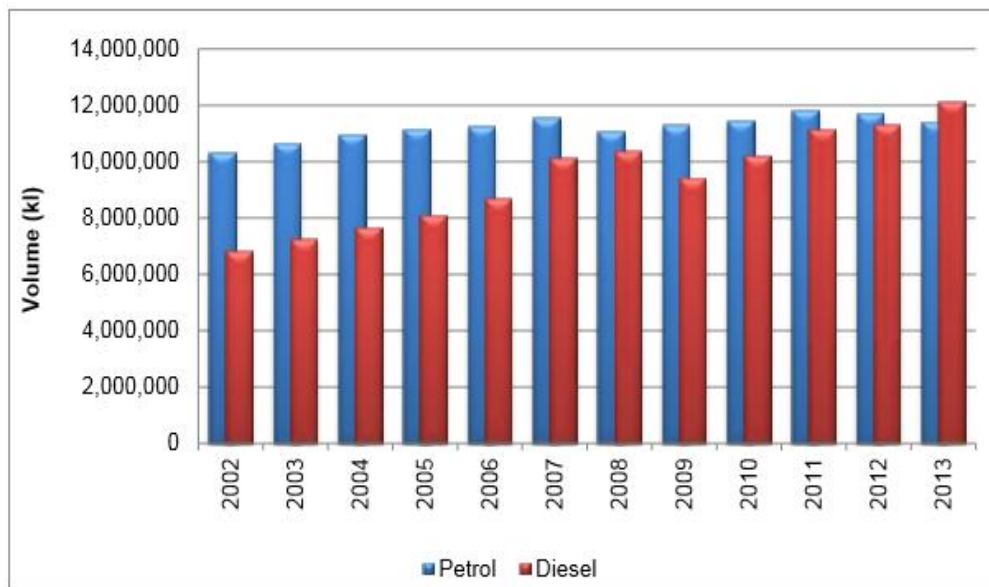
generation capacity of 52 GW will be from renewable sources [3]. Unfortunately, this progress is under threat by challenges being experienced at Eskom, the national power utility. Owing to low economic growth, the power utility is experiencing a period of demand stagnation and decline at a time that it is saddled with the construction of huge coal fired power stations (Medupi 4 764 MW and Kusile 4 800 MW) that have experienced delays and cost over-runs. This scenario has forced the power utility to implement higher tariffs which will further trigger lower consumption leading to a higher demand decline [4]. The finance minister, Mr Gigaba, recently indicated that Eskom currently has a surplus capacity of 5 GW [5]. The latest Medium-Term System Adequacy Outlook estimates an excess capacity on low demand scenario [6].

A combination of the competitive nature of the new RE capacity due to falling prices occasioned by better technology and improved efficiencies, and the cost associated with running the old coal fired power plant which now exceed the value of the stations to the electricity systems (not to mention the concern for the environment), has led to suggestions in some fora that most of these coal fired power plants be decommissioned before their due date [7]. However, this is unlikely to happen because of the social impact on employment and other political considerations.

While electricity generation is experiencing a glut, domestic production of transport fuel has stagnated. Production was 20.2 billion litres in 2002 but slowed to 19.7 billion litres in 2013 due to limited resources and capacity constraints [8]. This stagnation took place against the backdrop of a 3% growth in demand over the same period. Over this period excess demand was met by imports which grew at the rate of 12% annually (see Figures 1 and 2).



**Figure 1:** Supply and demand of diesel, 2002-2013



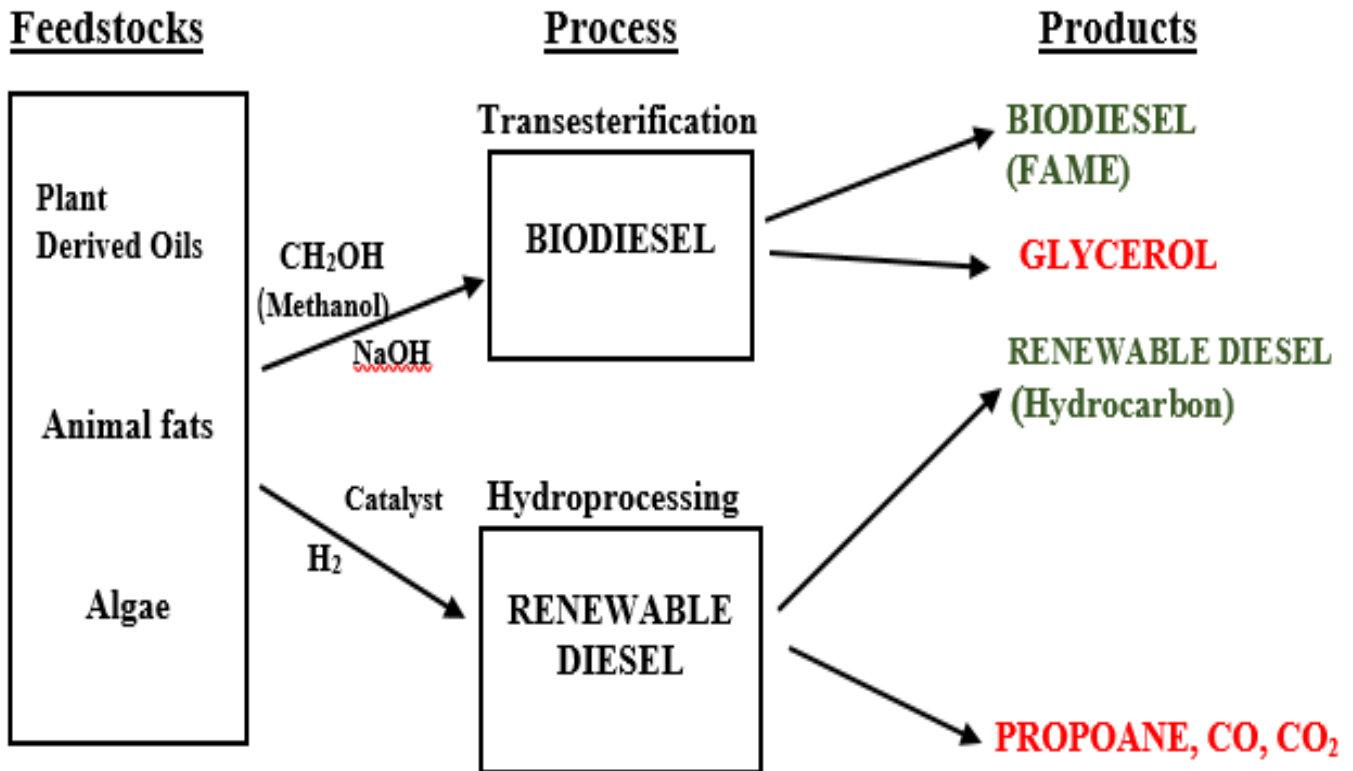
Source: Department of Energy (DOE)

**Figure 2:** Petrol and diesel consumption, 2002-2013

Attempts have been made through the Biofuels Regulatory Framework (Act No. 34 of 2008) to initiate the commercial production of renewable fuels, but not much has been observed in that sector due to embedded technical and economic factors [9]. Bearing in mind this context, this paper suggests a technology that can produce affordable, technically superior and completely renewable biofuel through the integration of the electricity and fuel refining sub-sectors.

Hydrogenation derived renewable diesel (HDRD) is a form of renewable diesel produced via the catalytic hydrodeoxygenation (hydrogenolysis) of vegetable oils, which

are triglycerides, into their corresponding paraffinic components which are alkanes. The glycerol chain of the triglyceride is hydrogenated to the corresponding alkane. The process removes oxygen from the oil and breaks the double bond resulting in straight chain fully saturated paraffinic alkanes [10]. HDRD can be produced from any vegetable oil or animal fat feedstock. This is the same type of feedstock already being used for biodiesel. HDRD does not discriminate on the basis of free fatty acid (FFA) composition as the latter is easily converted into paraffin during the hydrogenation process [10]. Figure 3 shows the production pathway for HDRD and biodiesel from a common feedstock.



**Figure 3:** HDRD and biodiesel production pathways

Some of the advantages of HDRD is that it is compression ignition (CI) engine compatible, the energy content and cetane numbers are higher than those of ultra-low sulphur diesel (ULSD) and biodiesel, its viscosity is lower than that of biodiesel, and, just like ULSD, it is not oxygenated. Finally, it does not contain sulphur.

Over 200,000 tons of used cooking oil is generated in South Africa annually [11]. Given the yield rate of 80%, 205 million litres of HDRD could be produced annually from this waste. This would supply 1% of the 2% set aside for the renewable fuel in the biofuel policy of the government in South Africa. Given the current price of used cooking oil (UCO) at R3 /litre and diesel at R14 /litre, a value added industry generating R2.04 billion can be created producing premium diesel (HDRD) along with the creation of thousands of jobs.

The aim of this paper is to evaluate the potential of integrating HDRD into the RE policy framework. This will involve, firstly, providing an overview of HDRD, describing the production process and how it aligns with the RE policy in terms of GHG (greenhouse gas) emission impact, cost implications (opex [operating cost] and capex [capital cost]) and feedstock recycling; secondly, comparing its superior quality with the available alternatives and what it means for capacity development and economic growth; and, thirdly, proposing a short and long term plan for HDRD integration into the energy architecture.

#### HDRD OVERVIEW AND DEVELOPMENT

HDRD is a second generation renewable diesel obtained from vegetable oil or animal fats via catalytic hydroprocessing. It is sometimes called green diesel or biodistillate. The feedstock for HDRD and biodiesel are the same, but the production pathways are different. The latter is done via transesterification hence the fuel obtained has a different composition and properties. The feedstock chemical composition is triglycerides which consist of a glycerol backbone and FFAs. The compound consists of varying carbon chain lengths and may or may not be fully saturated [12].

HDRD has some important advantages over biodiesel in terms of chemical composition, because biodiesel is made up of fatty acid methyl esters that contain some degree of unsaturation making it susceptible to oxidation, which poses challenges during transportation and storage, but hydroprocessing of triglycerides to produce HDRD results in paraffinic hydrocarbons which are fully saturated. Biofuel feedstock comes with varying degrees of FFA content. During transesterification to produce biodiesel, the FFAs in the feedstock react with alkali catalysts to form soap, an unwanted reaction. Feedstock with FFA > 13% by weight are not recommended for use in biodiesel production [12]. Conversely, FFA content is not a challenge in HDRD production as FFAs are easily converted to paraffin [10]. Other advantages of HDRD over diesel and biodiesel are evident in the properties listed in Table 1.

**Table 1:** Properties of ULSD, biodiesel and HDRD[10]

| Property                                | No. 2 Petroleum ULSD | Biodiesel (FAME) | Renewable Diesel |
|---|----------------------|------------------|------------------|
| Carbon, wt%                             | 86.8                 | 76.2             | 84.9             |
| Hydrogen, wt%                           | 13.2                 | 12.6             | 15.1             |
| Oxygen, wt%                             | 0.0                  | 11.2             | 0.0              |
| Specific Gravity                        | 0.85                 | 0.88             | 0.78             |
| Cetane No.                              | 40-45                | 45-55            | 70-90            |
| T <sub>90</sub> , °C                    | 300-330              | 330-360          | 290-300          |
| Viscosity, mm <sup>2</sup> /sec. @ 40°C | 2-3                  | 4-5              | 3-4              |
| Energy Content (LHV)                    |                      |                  |                  |
| Mass basis, MJ/kg                       | 43                   | 39               | 44               |
| Mass basis, BTU/lb                      | 18 500               | 16 600           | 18 900           |
| Vol. basis, 1000 BTU/gal                | 130                  | 121              | 122              |

The main focus of hydro-treating triglycerides is to remove oxygen and to saturate C=C double bonds resulting in the production of paraffin n-alkanes in the diesel boiling range. At high temperature and pressure, hydrogen reacts with triglycerides in the presence of a suitable catalyst resulting in the breaking of the double bond in the fatty acid chain. Subsequently, the glycerol backbone is broken by removing the oxygen, leaving paraffin n-alkanes [10]. Two alternate pathways exist to remove oxygen: hydrodeoxygenation (HDO) which requires sixteen moles of hydrogen to produce one mole of propene, six moles of water and HDRD, and the second is decarboxylation (DCO) which requires seven moles of hydrogen to produce one mole of propane and three moles of

carbon dioxide in addition to HDRD. HDO gives 5% more liquid fuel yield than DCO [13].

CanmetENERGY labs were among the first to develop technology for the hydrotreatment of renewable feedstock to HDRD. Its first patent, SUPERCETANE™, was established in the early 1990s [10]. HDRD commercialization began in the early to mid-2000s. Neste Oils' NExBIL and UOP's Ecofinning pioneered that technology. ConocoPhillip's Whitegate refinery at Cork, Ireland, was the first co-processing plant to come online in 2006 with a capacity of 57 ML/year HDRD facility. As of 2012, total global capacity for HDRD stood at 3.3 billion litres per year [10] (see Table 2).

**Table 2:** HDRD plants and capacity

| Company  | Location of facility   | Status      | Start date | Capital costs (USD) | Principal feedstock used                | Capacity (ML/yr)   |
|--|------------------------|-------------|------------|---------------------|---|--------------------|
| Nestle oil   | Porvoo, Finland        | Operational | 2007       | 130 million         | Palm oil<br>Animal fats<br>Rapeseed oil | 215                |
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| Nestle Oil   | Tuas, Singapore        | Operational | 2011       | 725 million         | Palm oil                                | 906                |
| Nestle Oil   | Rotterdam, Netherlands | Operational | 2010       | 1 billion           | Palm oil<br>Animal fats<br>Rapeseed oil | 906                |
| Dynamic Fuels (Syntroleum and Tyson Foods joint venture) | Geismar, Louisiana     | Operational | 2010       | 150 million         | Animal fats<br>Soybean oil              | 283                |
| <b>TOTAL EXISTING CAPACITY</b>                           |                        |             |            |                     |   | <b>2,525 ML/yr</b> |

|  |                       |                                 |                               |             |                            |                    |
|--|-----------------------|---------------------------------|-------------------------------|-------------|----------------------------|--------------------|
| Valero and joint venture                           | Norco, Louisiana      | Under construction              | Estimated start date: Q4 2012 | 300 million | Animal fats<br>Soybean oil | 509                |
| <b>TOTAL EXISTING + FUTURE CAPACITY (FIRM)</b>     |                       |                                 |                               |             |                            | <b>3,034 ML/yr</b> |
| UPM biofuels                                       | Lappeenranta, Finland | Construction begins summer 2012 | Estimated start date: 2014    | 200 million | Tall oil (pine)            | 117                |
| <b>TOTAL EXISTING + FUTURE CAPACITY (POSSIBLE)</b> |                       |                                 |                               |             |                            | <b>3,151 ML/yr</b> |

Other feedstock such as lignocellulose feedstock derived from agricultural and pulp/paper residue can also be used to produce HDRD, provided additional processing is undertaken to break up the cellulose, hemicellulose and lignin into smaller molecules. This can be achieved via pyrolysis, using thermal or catalytic depolymerisation [10]. This offers a huge opportunity for South Africa as it has a thriving pulp and paper industry existing side by side with a very successful commercial agricultural sector. This is an important advantage because, it has already been established that growing crops on a large scale for biofuel production is not feasible due to the water scarce nature of the country. Feedstock from use cooking oil and other renewable waste are the only viable path to green diesel production in the foreseeable future. Integrating it into RE policy also look promising.

An important factor in the planning for green diesel production is feedstock source. Most of the earlier plant installation had relied on traditional source of feedstock for biodiesel production. As will be expected, those sources were expensive. Generally, waste cooking oil is 2–3 times cheaper than vegetable oils [11, 12] and has become a promising feedstock in biodiesel production [13]. However, very few works have been performed producing green diesel from WCO. Overall, the key decider of hydrotreatment outcome is the selection of catalyst. The selection of catalyst is a critical step defining the yields and corresponding quality of hydro-processing products. In general, hydro-processing catalysts consist of critical metals such as Mo, Co, and Ni, as active metals and are usually supported by alumina or silica alumina [14]. During hydroprocessing, two possible processes, hydrotreating and hydrocracking may occur simultaneously. For diesel range fuel, hydrotreating process is favored which removes hetero atoms and saturate C–C bonds with the number of carbon atoms intact. On the other hand, hydrocracking (severe form of hydroprocessing) favours breakage of C–C bonds, drastically lowering the molecular weight to generate gasoline range fuels. Therefore, if the purpose is to get diesel fuels, then catalysts and reaction conditions should be properly selected that would result in hydrotreating of the feeds with minimal hydrocracking [15]. A combined sulfided Ni–Mo/Al<sub>2</sub>O<sub>3</sub> catalyst offers a high selectivity for diesel range (C<sub>15</sub>–C<sub>18</sub>) product from a mixture of waste soya oil and gas-oil due to minimal cracking, while a sulfided Ni–W/SiO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub> catalyst gives considerable jet range product due to cracking [16].

Another important consideration is the route taken for the hydro-processing. According to Zhang et-al [17] Several routes based on hydrotreating of vegetable oil have been implemented to produce biofuels from feedstock. Among these routes, two-

step processes are industrially available. Hydrodeoxygenation (HDO) is firstly employed to produce long-chain paraffins, followed by a hydroisomerization-hydrocracking to improve the cold flow properties in another reactor. Kim et-al [18] in their work studied various parameters in the catalytic hydro-processing of palm oil to maximize the production of biojet fuel. The results showed that the deoxygenation of triglyceride via hydrotreatment should be carried out in a separate reactor prior to the hydrocracking step (i.e., two-step reaction process). Otherwise, the CO generated during deoxygenation can poison the metal components in the metal/acid bifunctional catalysts (Pt/zeolites), which can cause significant imbalance between the metal and acid functions in hydrocracking. This leads to fast catalyst deactivation via coke formation, heavy formation of aromatics, and overcracking of hydrocarbons, resulting in the reduction of final biojet fuel yield. Recently, many works have been conducted to develop a one-step process to prepare bio-jet fuel from lipids. In these cases, HDO and hydrocracking occurred in a reactor. Sinha and co-workers [19] investigated the bio-jet fuel production from jatropha oil catalysts by a single-step route using hierarchical ZSM-5-supported NiMo or NiW catalysts. The choice of route and the type of catalyst employed will be determined by cost and feasibility with overall objective of obtaining optimal yield of green diesel.

Processing parameter are the means by which the process is controlled to yield the desired outcome. These parameters include the following; temperature, pressure, weight hourly space velocity and hydrogen/oil ratio. Patil and Vaidya [20] in their work to study the production of hydrotreated Jatropha oil using Co–Mo and Ni–Mo catalysts observed that using reaction variables as follows: temperature, 563–653 K; pressure, 1.5–3 MPa; H<sub>2</sub>/oil ratio, 200–800 (v/v); and weight hourly space velocity, 1–4 h<sup>-1</sup>. Oil conversion was maximized (Co–Mo, 97%; Ni–Mo, 88.6%) at T = 653 K and P = 3 MPa. The hydrocarbon yield at these conditions was 62.6% (Co–Mo) and 63% (Ni–Mo).

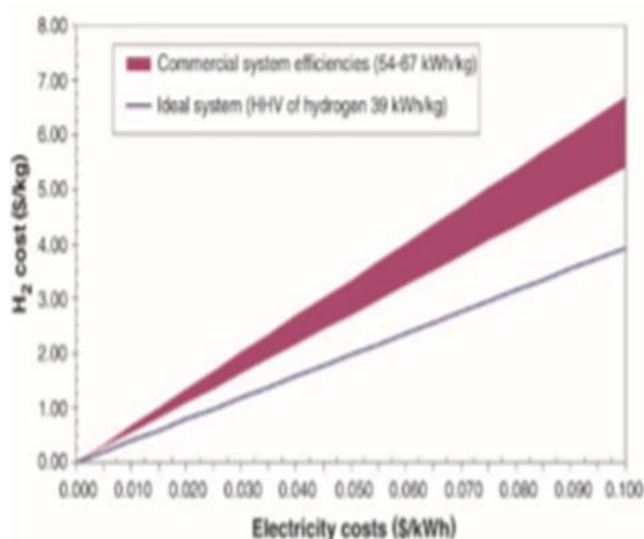
An important component of hydro-processing is hydrogen. Hydrogen is the most abundant element on earth. It combines readily with other chemical elements to form other substance, such as water, hydrocarbon, or alcohol. Hydrogen is also found in natural biomass, which includes plants and animals. Hydrogen is often considered as an energy carrier and not as an energy source.

A wide range of methods can be used to produce hydrogen, these includes; domestic resources, nuclear, natural gas and coal, biomass, and other renewable (solar, wind, hydroelectric, or geothermal energy) sources. These diversity of domestic energy sources makes hydrogen a promising energy carrier and

important for energy security. The production of hydrogen can be achieved via various process technologies, including thermal (natural gas reforming, renewable liquid and vegetable oil processing, biomass, and coal gasification), electrolytic (water splitting using a variety of energy resources), and photolytic (splitting of water using sunlight through biological and electrochemical materials).

The annual production of hydrogen is estimated to be about 55 million tons with its consumption increasing by approximately 6% per year. Hydrogen can be produced in many ways from a wide range of sources. Currently, hydrogen is mainly produced by the steam reforming of natural gas, a process which leads to massive emissions of greenhouse gases [21, 22]. Close to 50% of the global demand for hydrogen is currently generated via steam reforming of natural gas, about 30% from oil/naphtha reforming from refinery/chemical industrial off-gases, 18% from coal gasification, 3.9% from water electrolysis, and 0.1% from other sources [23]. Electrolytic and plasma processes demonstrate a high efficiency for hydrogen production, but unfortunately they are considered as energy intensive processes [24].

Given the current global focus on energy renewability and sustainability, the various pathways for hydrogen production faces significant challenges in meeting those stated criteria. The finite nature of crude oil and the large emissions observed with natural gas reforming makes hydrogen production from this source unsustainable on the long term. Coal gasification is a potentially huge source of hydrogen because of the large coal deposits across the globe and its relatively low cost [25]. However, to ensure environmental sustainability, the energy required for the sequestration of CO<sub>2</sub> would increase the rate at which coal reserves are depleted. Hence, this production source is also unsustainable. Solar derived, wind, nuclear, and geothermal energy are major resources for sustainable hydrogen production but, because of the unit cost of electricity the resulting cost of production is still a challenge (see figure 4 for hydrogen cost profiled against cost of electricity).



**Figure 4:** Hydrogen cost profile matched against electricity cost [26]

Although biomass is clearly sustainable, it cannot supply hydrogen in the amounts required. In addition, growing crops to produce fuel in a world where access to basic food is still a challenge, will attract significant resistance.

Another method available for hydrogen production is water pyrolysis. The direct thermal splitting of water requires temperatures of approximately 2000°C and produces a rapidly recombining mixture of hydrogen and oxygen [27]. A number of thermal chemical cycles have been identified that can use lower temperatures and produce hydrogen and oxygen in separate steps. The one that has received the greatest attention involves sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) at 850°C and hydrogen iodide (HI) at 450°C [28]. The next generation of fission reactors includes designs that can provide the necessary heat; however, a number of critical material properties must be satisfied to meet the required stability under the operating conditions of HI and H<sub>2</sub>SO<sub>4</sub>. But concern regarding nuclear proliferation and waste handling (which are hidden operating cost) ultimately makes this source unsustainable on the longer term.

Solar thermal systems could also be used to drive such thermal chemical cycles, although more interesting cycles involve the use of metal/metal oxide systems, in which solar heat is used to convert an oxide to the metal (releasing oxygen), and then the metal is reacted with water to produce hydrogen and reform the oxide [29].

Another source is via electrolysis. Any technology that produces electricity can drive an electrolyser to produce hydrogen. But cost is a challenge with this source because of the cost of electricity. Improvements in the efficiency of electrolysis are not going to lead to major reductions in the cost of produced hydrogen.

The energy required to split water can be obtained from a combination of heat and electricity. At 25°C, there is enough heat in the environment that the electricity requirement drops to 1.23 V. Increasing the electrolysis temperature can lower the electrolysis voltage, but the total amount of energy required to split water remains relatively constant. Thus, higher-temperature electrolysis only makes sense if the heat is free and it only requires a small amount of energy to move it where you need it, or there is an advantage in a new material set or a significant decrease in the electrolysis energy losses. The amount of water needed to produce hydrogen for transportation is not great. Conversion of the current U.S. light-duty fleet for example (some 230 million vehicles) to fuel cell vehicles would require about 100 billion gallons of water/year to supply the needed hydrogen [30]. Domestic personal water use in the United States is about 4800 billion gallons/year. The U.S. uses about 300 billion gallons of water/year for the production of gasoline [31], and about 70 trillion gallons of water/year for thermoelectric power generation [32].

Solar and wind power do not require water for their electricity generation. So not only do these resources provide sustainable carbon-free energy, they reduce the water requirements for power generation. Impurities in the water can significantly reduce the lifetime of the electrolysis cell. Water is usually



purified on site, but water clean-up could add to the cost of the hydrogen. In a stationary system where hydrogen is used for energy storage, the water from the fuel cell could be cycled back to the electrolyser with minimal purification. Sustainable hydrogen production technologies that may affect hydrogen production in the future include photo-biological [33] and photo electrochemical approaches [34–35]. These systems produce hydrogen directly from sunlight and water, and offer the possibility of increasing the efficiency of the solar-to-hydrogen pathway [36] and lowering the capital cost of the system, but they still require land area to collect sunlight. These systems might allow the use of sea water directly as the feedstock instead of high-purity water but these technologies are still at the research level.

From the evolving scenario, it is clear that at some point in the future the hydrogen economy will replace the hydrocarbon economy when the right hydrogen producing platform is established. But before that, a transition period will be observed. Past experience has indicated that this period could be between 75 to 100 years depending on how fast developments occurs. What is needed is a bridge technology for hydrogen production that is renewable and environmentally sustainable, which essentially feeds into the green economy narrative. Methane cracking provide such technology.

Methane cracking could be deployed as a bridge technology. In this process, methane is decomposed under high temperature and in the absence of oxygen to produce elemental carbon and hydrogen. The reaction generates zero emission [37-39]. For the hydro-processing of used cooking oil into green diesel, the methane can be obtained from anaerobic digestion of municipal waste as part of an overall strategy to beneficiate cities waste disposal system. In this cracking process, the molecular components of methane – hydrogen and carbon – are separated at temperatures of over 750° C (1,382° F), without harmful emissions. The concept of methane cracking has been around for several decades, but was limited by low conversion rates and carbon clogging. In a recent ground breaking feat, researchers tweaked the process using a novel 1.2-meter-high reactor design based on liquid metal technology, and made of quartz and stainless steel. Fine methane bubbles are injected into columns of molten tin. As they rise to the surface, the carbon was separated out and deposited as powder at the top end of the reactor. Clogging was avoided due to the easily separated micro-granular carbon powder, while the reactor's design makes it resistant to corrosion [40]. The team's research showed that methane cracking is comparable to water electrolysis, in regards to CO<sub>2</sub> emissions per unit of hydrogen, and more than 50 percent cleaner than steam methane reforming technologies. Further research in this area is ongoing to determine the scalability of the process for commercial application.

## **HDRD INFRASTRUCURE AND RE POLICY**

The momentum toward RE is irreversible. The green economy approach, sustainability, and energy efficiency, clearly have

been found to have positive impact on inclusive growth [41]. South Africa's refining capacity is ageing and given global trends toward renewable energy, some of those facilities are unlikely to be replaced with the same fossil feedstock. There are six refining facilities with approximately 750,000 bbl/day refining capacity and a natural gas to liquid facility in the mix [42]. The feedstock consists of imported crude, natural gas and local coal deposits. The vision of an economy driven by renewable energy as set in the energy policy has recorded significant success with electricity generation. This success needs to be replicated in the transport sub-sector to open up more opportunity for economic growth. To facilitate this, a transition mechanism must be in place for green hydrocarbon use.

At the moment, the biofuel policy has not gained sufficient traction. Currently there are eight biofuel plants in South Africa [43]. The volume of biofuels being produced from these plants is not sufficient to make any impact on the 2% blending mandate set by the biofuel energy policy [9]. The value chain of the biofuel industry is currently bedevilled by several challenges. Biodiesel will have a difficult future in South Africa because of a combination of factors, namely, water scarcity, fatty acid methyl esters (FAME) technical challenges in IC, and the unpopularity of converting food to fuel via a hefty subsidy in a country with food security challenges amongst the poor. Green diesel from waste appears to be a viable pathway to producing environmentally friendly transportation fuel.

## **HDRD enablers**

For the local production of green diesel (HDRD) to be successful, it is important to evaluate the factors that will create an enabling environment. HDRD needs easily available feedstock at a competitive price. Other parameters include: hydrogen, refining capacity (if it is via co-processing), a regulatory framework and government intervention that attracts investment (in the form of capex opex). Existing HDRD plants around the world have shown that feedstock accounts for 80% of opex while other inputs such as hydrogen, energy input/utility, water, catalyst and chemicals account for 15% [10]. Management, employee, and administrative costs account for the remaining 5%. The capex for a large sized HDRD plant is in the region of \$30 000 /bpd to \$40 000 /bpd. This is twice the cost of petroleum refinery which is between \$15 000 /bpd to \$20 000 /bpd [10].

The primary source of feedstock for HDRD is used cooking oil (UCO). Currently South Africa generates more than 200 000 ton/annum of UCO. This is essentially yellow grease. With added processing facilities, an additional 30 000 tons of brown grease can be removed from municipal solid waste (MSW). The price of UCO currently averages R3 /litre to R4 /litre. Legislation on banning the recycling of UCO for human consumption could keep a downward pressure on that price level. Other potential secondary sources of feedstock are cellulosic from pulp and paper industries plus a diverse range of agricultural waste with a far greater capacity than UCO.

Another important input is hydrogen. Hydrogen is an energy carrier. As stated earlier, it can be produced from fossil fuels, nuclear, solar, wind, biomass, hydro, geothermal and urban waste resources [44]. This is where the greatest opportunity exists for the RE policy to be integrated into the biofuel policy. If a policy framework is in place for green cars of the future, excess electricity can be used to produce hydrogen on an industrial scale and the RE sector can grow unhindered. The hydrogen sources for HDRD need to be green for the value chain to be completely green. Currently hydrogen from electrolysis is 1.5 times the cost compared to hydrogen from natural gas (which is the primary means of sourcing hydrogen). The most beneficial source of hydrogen for HDRD in South Africa is Municipal waste (MSW).

Hydrogen can be produced from MSW via anaerobic digestion of the compost portion to yield 50% to 70% CH<sub>4</sub>. Subsequently, using a thermal catalytic process, a transition metal catalyst is deployed to split carbon from carbon hydride (CH<sub>4</sub>) gas. The by product, carbon Nanofibre (CNF), has good morphology and high crystalline structure and its commercial value is an added bonus to the process [45]. An added advantage of this process is that it is achieved at a comparatively low temperature of 350°C, as oppose to the conventional Kvaener process at 1600°C (which is the most common means of obtaining hydrogen from hydrocarbon). According to the National Waste Information Baseline report (2012), South Africa generated 10.8 million tons of waste in 2011 [46]. This figure amounts to 295 890 tons per day. Given the established correlation that 70% of this waste is biodegradable, a hydrogen yield of 394 520 ton/annum can be obtained. Another upside to this data is the fact that the CNF yield from this process will be 1.183 Mton/annum and given CNF's current global price of R840.80/kg, a potential return of approximately R1 billion could be generated from this by-product alone.

### **Regulatory intervention and policy drivers**

The growth of RE in the electricity value chain in South Africa stands out as a good example of how regulatory intervention and good policy drivers can birth and ensure the sustainability of a viable industry. A well calibrated eclectic mix of policy documents, legislative frameworks and strong institutions working alongside research institutions have been able to build a platform for an expanding sub-sector with a strong human capital development component. One important component of the success factor was the start-up point. Implementation commenced with the 'low hanging fruit', that is, the country took advantage of opportunities in the areas it had a comparative advantage, namely, the solar and wind RE sectors. South Africa's solar radiation of between 4.5 kWh/m<sup>2</sup> and 6.5

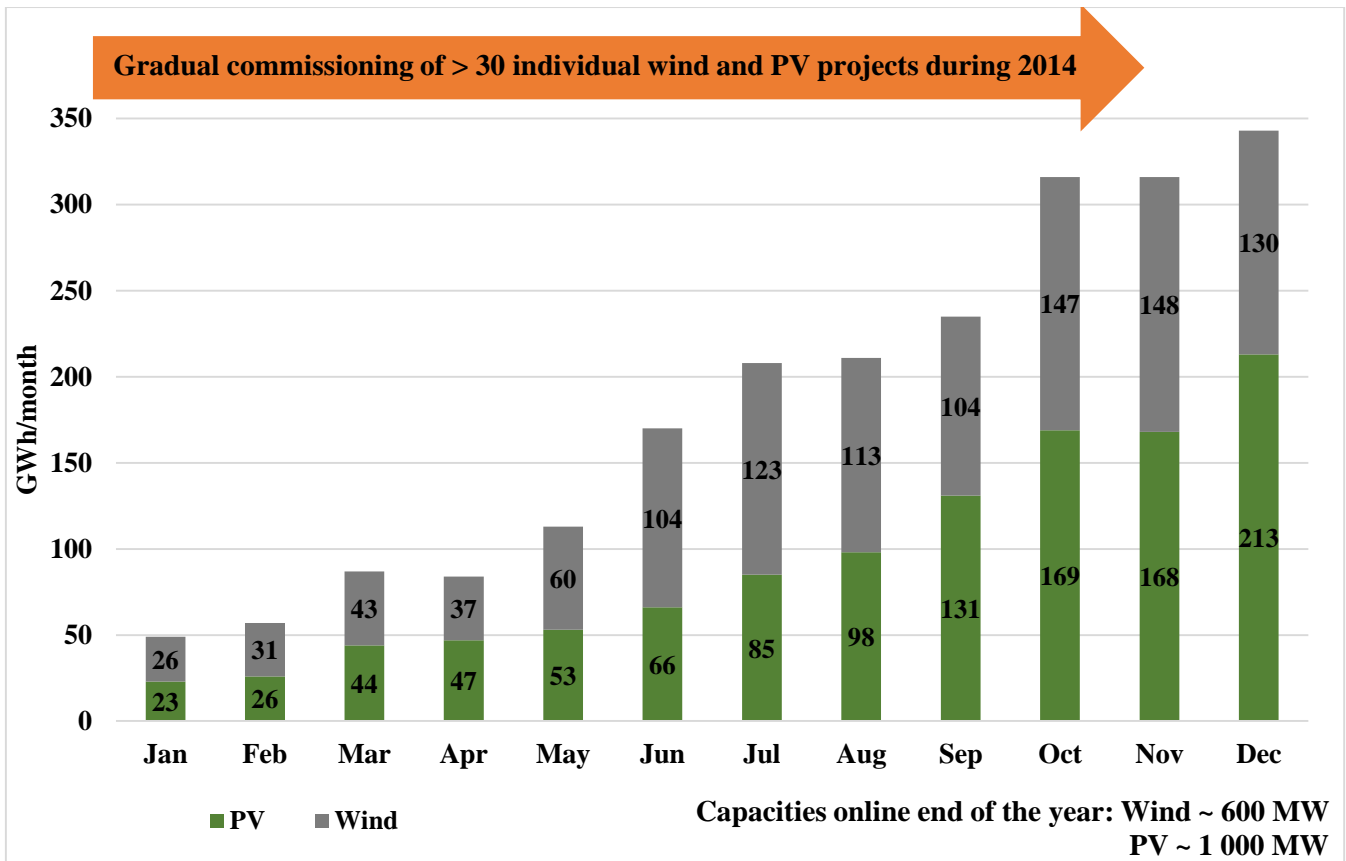
kWh/m<sup>2</sup> per day places it among the top three in the world [3].

The policy foundation was robust, being based on elements of the 1996 constitution that identified universal access to energy as a national goal that could potentially bridge income inequality. A white paper on energy policy (WPEP) in 1998 gave further interpretation. By 2003, a white paper on renewable energy (WPRE) was produced [3]. 2011 saw vital pronouncements on national climate change policy and a national development plan (NDP). The WPEP recognized the rapid development of renewable energy technology (RET) across the globe and set out from the start to take advantage of the opportunities. The WPRE set targets for RETs in financial instruments, legal instruments, technological development, governance, capacity building, and education.

Another component that helped facilitate RE growth in the electricity sub-sector was the presidential undertaking at Copenhagen in 2009 to reduce emissions in South Africa by 34% by 2020, progressing to 42% by 2025 [3]. This led to the crafting of the National Climate Change Response White Paper (NCCRWP). This document became the instrument deployed to mitigate emissions in the transport and energy sector. In 2011 the Department of Energy (DoE) published the integrated resource plan (IRP) 2010-2030 which provided long term plans for electricity generation. The plan called for a doubling of installed capacity. The synergy of the Electricity Regulation Act (ERA, 2006) as amended and the Energy Independent Power Producer Procurement Programme (REIPP) was also vital. The ERA and its regulations enable the Minister of Energy to determine what new capacity is required, otherwise the allocated quantity is derived from IRP 2010-2030. A target of 17 800 MW new generation capacity was set aside for renewables.

Price determination via tariff was another component that was adequately provided for. In 2008 South Africa introduced renewable energy feed-in-Tariffs (REFIT) to facilitate RE. In 2009, the National Energy Regulator of South Africa published REFITs with proposed tariffs designed to cover generation cost plus a real after tax return on equity (ROE) of 17%. This generated instant market interest and was described as the 'tipping point' for RE. A competitive bidding process was adopted to keep the price down while providing incentives for market entry by investors. The procurement process started in August 2011. By November 2011, 28 appointments had been made offering about 1 416 MW, with total investment of close to US\$6 billion. Some projects came on stream by the end of 2013 and an additional 36 RE IPPs were selected as preferred bidders by October 2013 [3]. As seen in Figure 4 below, the growth trajectory in RE for electricity has been sustained since then.





**Figure 4:** REIPP growth in energy produced during 2014 (Eskom, CSIR Energy Centre analysis)  
 Source: Eskom, CSIR Energy Centre analysis

What this experience underscores are the need for industry to engage in due diligence prior to any significant progress in RE build-up in any sector. Although biofuel is an integral part of the RE policy, due to the absence of planning, policy frameworks that identify suitable technology, and industry wide collaboration, the sector has been relegated to a footnote in RE policy implementation. Challenges in the biofuel sector are numerous and could have been responsible for the low appetite from key players, but what is obvious is that to achieve a green economy of the future and generate more scope for economic and employment growth, the biofuel potential cannot be overlooked.

The government has previously identified the potential of biofuel to generate employment. In 2005, Cabinet mandated the then Department of Minerals and Energy to lead and coordinate a biofuel industrial policy. A proposal to blend 2% biofuel into the total fuel needs was approved 5<sup>th</sup> December, 2007. This was part of a five-year plan (2008 – 2013). Bio-ethanol was projected to be 393 million litres per annum and biodiesel was to be 970 million litres per annum. This policy proposal, unfortunately, did not produce a single large plant due to non-viability, financially, of biofuel at the prevailing hydrocarbon price. To address this challenge, the Department of Energy (DoE) was mandated to create financial attractiveness. The DoE in collaboration with the Biofuel Task Team (BTT) was tasked with the goal of implementing, monitoring and refinement of biofuel policy through the creation of a

regulatory environment conducive to biofuel production. A mandatory blending policy was promulgated in 2012 including guidelines on licencing of manufacturers [9].

To tackle the price challenge, a pricing framework and reference crop was considered. The goal was to guarantee a return on asset of 15% (ROA). A government incentive was also proposed to plug the gap between market value and earning required to achieve the 15% ROA. A decision on feedstock was also reached; sorghum and sugar cane were chosen for bioethanol and soya beans for the production of biodiesel [3]. Criteria for eligibility for government support was also stated. Eligibility was to be on a first-come, first-served basis, subject to meeting pre-determine economic criteria. The subsidy was also to be based on the actual fuel blended. A decision on revision of the subsidy mechanism for penetration level above 2% was to include stricter criteria for food and water security as well as environmental impact. Biofuel levy collection, administration and disbursement was to be conducted via the Department of Energy (DoE) in conjunction with the South African Revenue Service (SARS). Blending was proposed to be conducted at refineries. The potential challenges with logistics associated with blending at refineries was significant. Transporting biofuel to refineries over a considerable distance would impact on the bottom-line. Pipeline transport was not feasible because of potential contamination to jet fuel.

In summary, the following are believed to be some of the factors that have inhibited progress in the biofuel sector:

- (i) The policy was not sufficiently crafted to provide price incentive that could attract investment.
- (ii) Sufficient research was not conducted to determine best fit technology to produce biofuel that aligns with already existing infrastructure. 'Low hanging fruits' were not targeted.
- (iii) Multi-sectoral collaboration and consultation were not robust enough to elicit interest and condense ideas.
- (iv) Legislation on biofuels in their present form do not provide sufficient safeguards to secure key inputs that facilitate the production of biofuel. An example is the recycling of used cooking oil for human consumption. Apart from the fact that this practise is detrimental to public health and safety, this provides competition for HDRD feedstock.
- (v) The decision to make access to government subsidy on a 'first come first served basis' rewards haste as opposed to due diligence in an industry that requires considerable effort to implement a successful project. And, given the inherent risk in the biofuel sector and the embedded potential to create employment, a government incentive of 15% ROA (below RE electricity by 2%) was inadequate.
- (vi) The process of crafting policy for the industry appears to be inflexible. This can be seen in the selection of feedstock and technology for the production of biofuel. UCO and HDRD were not mentioned in the document in spite of the fact that the country has significant refining capacity, is well urbanized (to generate considerable UCO), and the cost of UCO is approximately ten time less than virgin cooking oil.
- (vii) The broader GHG mitigation strategy through the instrument of carbon tax and carbon credit that could have also served as important facilitators of the biofuel industry has not been fully rolled out.

## THE HDRD PROPOSAL

The focus of this piece is to draw attention to the potential of HDRD in South Africa and to suggest an integration pathway for green diesel production in the RE policy and growth trajectory.

The scope for HDRD integration into the RE electricity sub-sector is substantial because of their overlapping technology, some of which includes:

- (i) Hydrogen (a feedstock for HDRD refining production) which could be produce from biogas obtained from municipal waste, direct water splitting or electrolysis.
- (ii) Municipal waste processing plant that produce CNF and hydrogen which could be powered by a solar or wind plant, and
- (iii) A cellulosic feedstock processing plant powered by either CSP (concentrated solar power), wind or solar plant that uses agricultural waste, wood waste, etc.

A potential pathway for green diesel production will involve easily implementable short term strategies and a more robust long-term programme.

## Short-term outlook for green diesel

To kick-start and generate sufficient momentum for a green diesel program, a simple plan requiring careful execution by industry players with vast knowledge in related technology with regulators (government) providing well calibrated incentive to minimize risk is hereby proposed. HDRD can be produced from a desulphurization unit of a refinery with basic reconfiguration of the catalyst bed [10]. For this to be possible, strong incentives must be provided to refiners through the mechanism of the carbon credit/tax and the general fuel levy subsidy stipulated in the biofuel policy [47]. In order to make the value chain completely green, additional incentives should be provided for sourcing hydrogen from MSW. Capital expenditure (Capex) for plant remodelling to accommodate HDRD should be subsidized to guarantee at least 20% ROA (3% more than for RE). Legislation that criminalizes the recycling of UCO for human consumption should be considered with vigorous enforcement penalties. The supply logistics for UCO should be incentivized to pull-in UCO from domestic sources and small time food vendors. The short-term strategy will rely on co-processing, incentivization, and regulation.

### i. Co-processing of HDRD

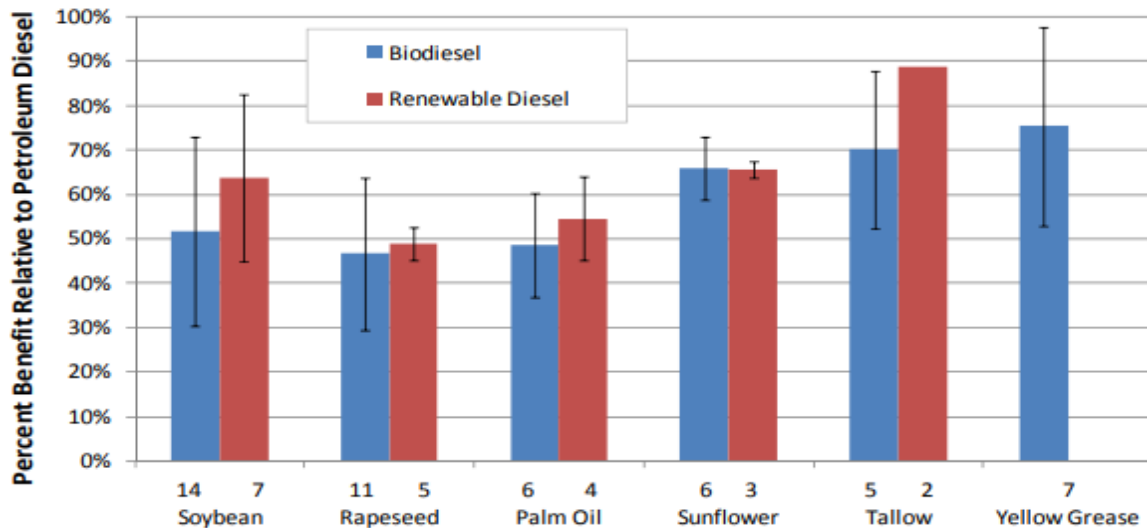
An important advantage of the HDRD production process is that it can make use of existing refining technology. Hydro treatment units are already used in conventional refineries to desulfurize fractional distillates, which include diesel fuels [10]. The same technology can be used for the hydro treatment of renewable oil to produce HDRD. The only thing that needs modification is the catalyst bed because the operating parameters and the catalyst used for diesel oil and renewable oil are different. This change over between operating mode takes time and careful planning, but with the right incentives, it can be implemented. The advantage of co-processing is the large saving in capex. The pioneer production of HDRD from UCO in South Africa would be best achieved via co-processing at a conventional refinery as a standalone HDRD facility can only be advantageous if large volumes are being handled.

In terms of cost profile, the renewable feedstock can be co-processed with petroleum feed using existing refinery infrastructure – the capex and opex are marginal. British Petroleum (BP) and Petrobras have installed such facilities in Australia and Brazil respectively and they have indicated that the marginal capital cost is minimal. The BP plant co-processes about 2 000 bpd HDRD and Petrobras adapted four of its facilities so that it can co-process up to 4 000 bpd of green diesel [48-50]. Petrobras revealed that capex to accommodate co-processing was about \$5.6 million. The only challenge observed was the cost of feedstock, but for South Africa this might not be a challenge as UCO is still relatively cheap at R3 /litre.

**(ii) Incentive and regulation for co-processing**

The primary push for green diesel has been its capacity to reduce GHG emission or global warming potential (GWP). Accordingly, incentives for its production across the globe and regulation of the industry has been determined by the extent to which positive GWP can be achieved. The GHG emissions that result from the production and use of HDRD can be calculated using well-to-wheel full life cycle analysis (LCA). Studies on LCA for HDRD are sparse at the moment but as the technology gains prominence more studies will become available, but from

the few that are available as shown in Figure 5, the GHG benefit for HDRD in comparison to diesel exceeds that of biodiesel in comparison to diesel by an average of 10%. Of particular note in the figure is that biodiesel GHG benefits for yellow grease (UCO) exceeded those of all other reported biodiesel derived from other sources. Although the HDRD equivalent for yellow grease was not reported, it is obvious that given the parameters evaluated, it will exceed those of tallow (which is the highest among the data presented in the figure) [3].



**Figure 5: GHG benefit graph**

What this implies is that incentives based on GHG benefits will yield more value for HDRD produced from UCO than virgin oil. This will be important when the carbon credit/tax mechanism comes into full implementation [47]. Other incentives stipulated in the biofuel policy such as fuel levy exemption and the import substitution waiver designed with bioethanol and biodiesel in mind may need to be revisited to configure the instrument for the purpose of yielding more incentives for HDRD. This is in addition to strong regulation blocking the recycling of UCO back into the human consumption food chain which will serve to promote the commercialization of green diesel.

**Long-term outlook for green diesel**

The long-term outlook for HDRD in South Africa will be determined by current trends in the pulp and paper industry, renewable electricity and global warming concerns. Currently, the recovery of timber from South African forests is 47%, compared with the world average of 60%; it is clear that the industry is less efficient, and a lot of waste is being generated [51]. Added to this is the increasing demand for pulp and paper which will in effect lead to an increase in waste being generated by the industry. The most economical use for this waste is biofuel (HDRD). The second trend is the falling price of RE electricity. In 2015 alone, the price of a large solar plant price

fell by almost 12% [52]. This trend is set to continue. Already electricity derived from RE solar PV is becoming competitive with conventional electricity sources. It is hoped that with improving technology, in the not too distant future, it is envisaged that the price of hydrogen derived from electrolysis will converge with that derived from natural gas. When this happens, it will clearly mark the end of the crude oil economy.

In the international community, discourse on global warming is becoming more strident, with access to capital for development of ‘dirty’ energy sources becoming increasingly difficult. This firming up of resistance against unmitigated emissions will increase to a point where direct sanctions against entities and sovereigns will be openly discussed [53]. The fuel transport segment of the economy needs to prepare for this future.

Stand-alone plants dedicated to the production of HDRD from agricultural and forest waste hold the key to providing the bridge technology and meeting the demand for renewable diesel in the future. Feedstock for such a plant/or plants will not only come from forest waste, but also from brown grease found in MSW.

**CONCLUSION**

Renewable energy is gaining a significant footprint in the new economy, driven by a range of challenges some of which

include environmental concerns, the need for sustainable growth, and the finite nature of fossil fuel. Tremendous progress has been made in renewable electricity, but biofuel growth has lagged behind in South Africa largely because the preferred technology is out-of-sync with the country's competitive edge. This presentation has identified HDRD as the technology platform with the most promising potential to actualize the national biofuel target. For this to happen, the right mechanisms ought to be in place to promote the idea. These include, but are not limited to, the following:

- (i) The inclusion of HDRD technology into the National Biofuel policy
- (ii) Regulations to promote and protect the sources of feedstock for HDRD.
- (iii) Incentivization of the production of critical inputs required for the production of HDRD.
- (iv) The carbon tax/carbon credit mechanism policy should be crafted to accommodate practices that promote industrial production of HDRD.
- (v) Wind farms and solar power plant that are solely dedicated to processing of cellulosic feedstock for HDRD or MSW to hydrogen feedstock should be further studied to determine their viability.
- (vi) Given its superior fuel quality, a scheme to popularize the benefits that green diesel brings to the IC engine and the environment should be undertaken.
- (vii) Government intervention should be calibrated to ensure that margins obtained from HDRD refining equal or exceed margins obtained from crude oil refining.

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