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2nd Generation Pure Plant Oils from Decentralized Oil Mills as Future Fuel for Flex-Fuel Common-Rail Engines in Rural Electri Fication and Agricultural Transport

Dr. Georg Gruber[1], [2]Alexander Koder, [3]Prof. Dr. Hans-Peter Rabl, [4]Hannes Blauensteiner, [5]Thomas Dotzer

[1]Vereinigte Werkstätten für Pflanzenöltechnologie Dr. Gruber/Gruber GbR Am Steigbühl 2, D-90584 Allersberg, Germany
[2]Ostbayerische Technische Hochschule Regensburg – Laboratory of Combustion Engines and Emission Control Galgenbergstr. 30, D-93053 Regensburg
[3]Ostbayerische Technische Hochschule Regensburg – Laboratory of Combustion Engines and Emission Control Galgenbergstr. 30, D-93053 Regensburg
[4]Waldland Naturstoffe GmbH,Oberwaltenreith 10, A-3533 Friedersbach
[5]Dts-design Lohbachstrasse 2e, D-91161 Hilpoltstein

Abstract: *Pure plant oil was closest to the diesel engine at the time of its invention. It is well known that Rudolf Diesel himself displayed a diesel engine running on groundnut oil at the Paris world exhibition in 1896. Up to now the quality of fuel and combustion engines increased constantly. Sustainable plant oils are an affordable, safe, social and environmentally friendly fuel supply, especially at countries of its origin, not only for generators and tractors but also for transport vehicles. State of the art today is an innovative decentralise production method for 2nd generation plant oil complying with DIN 51623 fuel quality and an engine technology for pure plant oil, biodiesel and diesel. Such innovative flex-fuel engines can be used for electricity production in stand-alone gen-sets or within a hybrid system of different renewable energies like wind power, photovoltaic, hydro power. Such a flex-fuel engine technology John Deere Europe has assigned for their tractors as future transportation concept for agriculture. Both, the new fuel quality and production method and the innovative flex-fuel engines can provide agriculture and remote areas with 100 % renewable energy for electricity and a wide range of sustainable plant oil fuels for tractors and rural machinery.*

Keywords: *Jatropha, pure plant oil, 2nd generation bio fuel, renewable energy hybrid system, flex fuel engine, DIN 51623*

I. Introduction

Over two billion of nowadays world population is living off-grid. Most of them are farmers and most of the inhabited off-grid areas are agricultural land. The dominant energy source for agricultural electrification and transport is diesel with often high cost and high environmental risk due to long and dangerous transport logistics. Fig. 1 shows the percentage of grids operated with diesel generators. A 100 % electricity supply with diesel generators is red-colored. Dark blue is the share of 0 % diesel generators of the worldwide grids. The higher the diesel share the more local diesel grids can be expected.

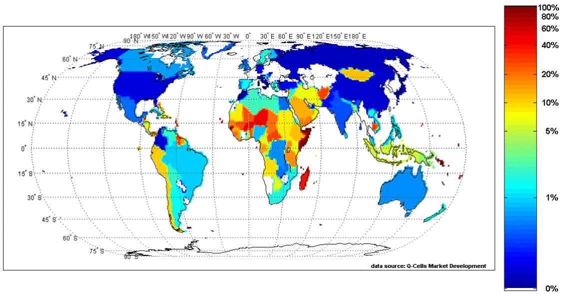

Figure 1 [1]**:** Share of diesel power plant capacity to total power plant capacity

Electricity and mobility from local renewable energies like hydropower, photovoltaic and biomass are a promising alternative to substitute fossil fuels. Biofuels from biomass have a major advantage to any other renewable energy because they are already stored energy.For rural electrification, engines running on biofuel can be used in stand-alone generators or in renewable energy hybrid systems as back-up system or as balancing electricity producer to regulate and compensate voltage and frequency fluctuations of the grid.

The same biofuel can additionally be used for agricultural machineries like tractors, trucks, pick-ups which cannot be replaced by electro mobility. Biofuels are especially suited for rural electricity and transport because agriculture can produce the biofuels by themselves. So, biofuels are a backbone in rural areas due to the possibility of feasible local production and consumption for electricity and mobility in context with other renewable energy systems. For safe, reliable and economic mobility and electricity production, VWP-Gruber and partners worked on a sustainable fuel supply and reliable engine and hybrid energy systems.

II. 2nd Generation Pure Plant Oils From Decentralized Oil Mills

Future biofuels require a holistic approach of a feasible, CO_2 efficient and sustainable production concept integrated into an application strategy of high-end common-rail engines with diesel, biodiesel, plant oil multi fuel capability, high fuel efficiency and low emissions at the same time. Biodiesel is plant oil which by transesterification is adapted to standard serial diesel engines. In contrary, to use pure plant oil as fuel, regular diesel engines have to be technically adapted for consumption of this high viscosity fuel. However, now, with the worldwide market appearance of modern common-rail engines and advanced exhaust gas after-treatment systems, also the utilization of biodiesel requires an engine adaptation. Therefore engine producers have drawn back approval for 100 % biodiesel usage for their advanced stage 3A, 3B and stage 4 engines. Since both biofuels require an engine adaptation, the pure plant oil concept has several advantages to the utilization of biodiesel. In comparison to biodiesel, pure plant oil is an ideal fuel for transportation and storage because it lacks hygroscopic and is considered as an inflammable and non-water hazardous product with higher energy content per liter (about 8 %) than biodiesel.

The direct utilization of pure plant oil in adapted diesel engines saves the whole chemical process of transesterification into biodiesel with substantial reduction in cost, CO_2 and transportation effort. The production of pure plant oil is a simple mechanical/physical pressing and filtering process with no methanol/ethanol demand and glycerin leftover. In comparison to other biofuels like alcohol, biogas or biodiesel, pure plant oil in advanced diesel engines is the combination of highest fuel density with highest engine fuel efficiency. For a long time, pure plant oil was considered as a non-future 1st generation fuel which can be used only in adapted simple TIER 1 and TIER 2 diesel engines. Due to the excellent physical properties of pure plant oil, VWP-Gruber, Dts Design and Waldland for many years focused on both the improvement of fuel quality and engine combustion technology. First fuel quality norms for pure plant oil (DIN V51605) and biodiesel (EN 14214) allowed a high content of alkali and earth-alkali like phosphorous (P), calcium (Ca) and magnesium (Mg). In DIN V51605 for pure rapeseed oil the limit for P was 12 mg/kg and for Ca/Mg 20 mg/kg [2]. Since P, Ca/Mg are found responsible for a reduced engine life span, poisoned catalytic converters and blocked particulate filters, VWP-Gruber and the Austrian company Waldland developed a new patent-protected oil production process to remove these minerals [3]. Fig. 2 describes the innovative process.

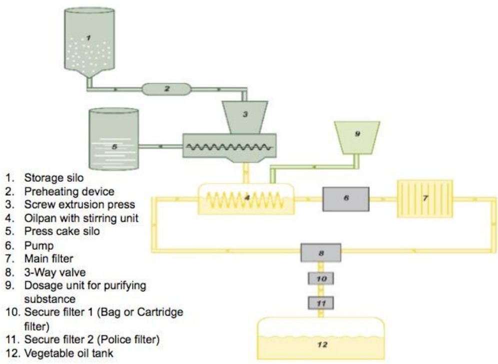

Figure 2: VWP/Waldland process for P, Ca/Mg cleaning.

Depending on the initial value of P, Ca/Mg in the crude oil and the desired reduction value in the clean oil, a particular combination of OBEFIL (filter and cleaning aid) dosage, stirring time, oil temperature and filtering effort is needed to reduce the content of P, Ca/Mg to the analytical limit of detection (< 0,5 mg/kg) [4]. The innovative P, Ca/Mg purification process therefore can undercut the latest DIN 51605 fuel quality for rape seed oil respective the latest DIN 51623 fuel quality for different plant oils. For both DIN norms the limited parameter for P are 1mg/kg and for Ca/Mg 3mg/kg [5]. Adding an oxidation stabilizer improves storage conditions even of tropical plant oils in warm environment for more than one year. Because of the simple production process, 2nd generation plant oil can be produced everywhere in Asia, Latin America, Africa and Europe next to plant oil fields and plantations. This gives agriculture and remote areas or islands worldwide first-hand access to a sustainable, regionally produced high quality fuel.

Fig. 3 shows a decentralized oil mill in Ecuador/Manabi with oil press, fuel filter system and P, Ca/Mg purification system.

Figure 3: Decentralized oil mill in Manabi with VWP/Waldland purification system

The oil mill is able to produce up to 400,000 liters/year complying with the latest and most challenging fuel quality standard for international plant oils as fuel, the DIN 51623 standard [5]. In Germany and Austria, more than 200 decentralized oil mills are in operation. Since 2011, the oil mill from Manabi produces jatropha oil from so-called living fences for a renewable energy hybrid system on the Galapagos Island Floreana. In a public private partnership project subsidized by the German Ministry for Development Aid, in 2016 VWP-Gruber and WWF Germany will apply for certification of the Manabi Jatropha Oil Association following the sustainability standard of RSB (Roundtable on Sustainable Biomaterials). The Manabi smallholder project is considered as one of the most interesting sustainable biofuel projects in presence [6]. Up to 3,000 family farmer members collect and transport jatropha nuts from already existing living fences and produce sustainable jatropha fuel with a low CO_2 footprint for Galapagos Islands with their own decentralized oil mill (see Fig. 4).

Figure 4: Jatropha nuts harvest and transport in Manabi/Ecuador

The Manabi jatropha oil project can be a blue-print for highest fuel sustainability standard since jatropha avoids the food versus fuel conflict with no additional agricultural land or rainforest used, without irrigation and chemicals and a full respect to gender and social and property rights [7].

III. Common-Rail Flex-Fuel Engines For Rural Electrification And Transport

Among other combustion engines like gasoline engines for alcohol or biogas, diesel engines achieve highest fuel efficiency rates. Therefore, VWP-Gruber developed a new generation of flex-fuel common-rail engines which, after mechanical and electronical adaptation, can be fueled with 2nd generation plant oils, biodiesel, diesel or blends of these fuels. Such innovative flex-fuel common-rail engines can be used for electricity production or agricultural machineries like tractors, trucks or pick-ups.

3.1 Development of Flex-Fuel Common-Rail, High Pressure Injection Engines for Electrification

In comparison to other liquid biofuels like alcohol or biomass to liquid (BTL), plant oils have got a 19-50 times higher viscosity at 20 °C which automatically prevents the fuel from evaporation.This feature plus their high flash point (> 300 °C) and relatively low cetane number (indicator of ignitability) makes pure plant oils absolutely explosion-proof and non-hazardous to water, soil and air. It is the natural properties of plant oils which make them an ideal fuel for transport, logistic storage and an obvious choice as a natural fuel for mobility and electricity. But exactly the natural parameters which lead to the legal risk classification "non-inflammable fuel" cause combustion problems within a diesel engine at the same time. Therefore, series diesel engines have to be technically adapted before being able to burn pure plant oils.

To adapt pure plant oil to the engine like the biodiesel process does, was no option for VWP-Gruber. Due to in biodiesel lowered parameters for viscosity, flame point and increased cetane number, the new plant oil fuel biodiesel loses its legally classification as "non-inflammable fuel" and non-hazardous for water with huge disadvantages for transport, storage and consumer risks. For adaptation of diesel engines to pure plant oil as fuel, no master adaptation kit exists which fits for all diesel engines. Moreover, since every diesel engine producer creates an individual diesel technology also the adaptation techniques have to follow these individual diesel designs with individual problem solving technologies. The following Fig. 5 describes the basic technical changes for a flex-fuel common-rail engine.

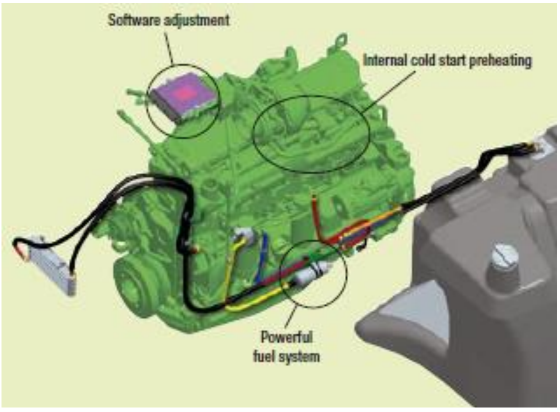

Figure 5: Basic adaptation for a common-rail engine [8]

- Powerful fuel supply with fuel detection system with automatic pressure and volume regulation as a function of changing fuel temperature and viscosity [9],
- internal heating device of injectors for improved cold start and emissions [10],
- software adaptation with different software architectures depending on required emission class [11]
- and actual fuel type [12].

After applying these basic and several individual adaptation measures, common-rail engines can perform multiple fuels (pure plant oil, biodiesel, and diesel) with one tank (flex-fuel) in stationary or mobile engines of different sizes. A tractor producer with this innovative all fuel engine technology was awarded with a gold metal at one of the internationally biggest agricultural fairs [13].

3.2 2nd Generation Pure Plant Oil for Electricity Production

Both, the new fuel quality and production method and the innovative flex-fuel engines can provide agriculture and remote areas with 100 % renewable energy for electricity or/and heat production.Already 20 years ago the first mountain bases operated by the German Alpine Society were supplied with both heat and power from stationary co-generation plants fuelled with pure plant oil. In 1996 the first 100 % renewable energy PV-battery-plant oil co-generation hybrid system based on an adapted series diesel engine was installed at about 2,800 m altitude to serve an alpine hut in the Austrian Alps with electricity and heat. Fig. 6 shows the Stüdl hut with photovoltaic elements on the roof and battery, pure plant oil co-generation and hybrid system switch board inside the small hut aside.

Figure 6: Alpine helicopter rapeseed oil fuel transport for adapted plant oil co-generation at Stüdl hut

Today in Germany, Austria and Switzerland more than 60 alpine huts are equipped with pure plant oil cogenerations as standard product in hybrid systems of batteries, photovoltaic, wind- and water power. On alpine huts only pre-chamber engines are used and only rape-seed oil as fuel which stays liquid up to temperatures of minus 10 °C [14]. In the following years, direct injection-engines, engines with high pressure injection and other plant oils than rapeseed oil have been developed for electricity production. A milestone project for electricity production with biofuels for agricultural or remote areas is the substitution of fossil fuels by renewable energies on the Galapagos Islands.

After severe ship accidents in 2001/2002 causing death of 10,000 iguanas and other marine species, the Ecuadorian Government has started the initiative “Zero Fossil Fuel for Galapagos Islands Until 2020”. In a feasibility study from German GIZ, out of different biofuels (biodiesel, pure plant oil, biogas/wood gas) and different plant oils (palm, rapeseed, jatropha, sunflower, soy) pure jatropha oil was chosen with the best environmental, social and economic balance as ideal fuel to comply with the highest technical and environmental requirements on Galapagos Islands [15].

In a pilot project and in cooperation with the Ecuadorian Ministry for Energy and Renewable Energy and the German Ministries for Environment and for Development Aid, VWP-Gruber installed two jatropha oil gen-sets on the smallest inhabited Galapagos Island Floreana in 2010 and maintained it until 2014. On Floreana Island, 100 % solar energy is used by combining photovoltaic and photosynthesis. 21 kWpeak photovoltaic harvests the actual solar radiation during the day while two 69 kWel. Generators using jatropha oil as stored solar energy build the grid and add electricity for peak electricity demand or for periods with no solar light or empty batteries. For more than 18,000 monitored hours for each flex-fuel engine, the jatropha oil gen-sets used 100 % jatropha, diesel or a blend and showed no technical failures. Fig. 7 illustrates the installed generators.

Figure 7: Jatropha gen-sets, 2 × 69 kWel on Floreana

The challenge on Floreana was to establish a 100 % renewable energy off-grid system whose electricity supply exactly covers the electricity demand of a constantly shifting 24 hours' daily load curve of Floreana Island. There are different scenarios and concepts for hybrid system operation to achieve highest PV penetration and lowest engine hour operation at low operational cost. The following Fig. 8 is the example of a scenario how the electricity demand over 24 h (red curve) can be satisfied by the interaction of PV supply (yellow), jatropha oil gen-sets (blue) and charging/discharging batteries (green). The not usable PV share (grey) can be used for a growing electricity demand in the future or for battery charging of electrically operated vehicles or boats.

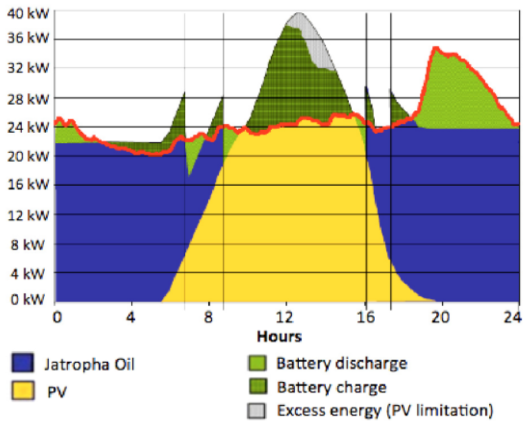

Figure 8: Simulation of Floreana hybrid concept [16]

Although, jatropha oil is considered as one of the most promising future fuels, there were almost no references for pure jatropha oil on long-term engine behaviour or emission results. In Fig. 9, the emission test results of the modified Deutz 1013 BF4M engines for dual fuel operation are displayed. The emission test was conducted on the island in January 2011 with a TESTO 350 M/XL emission tester [17].

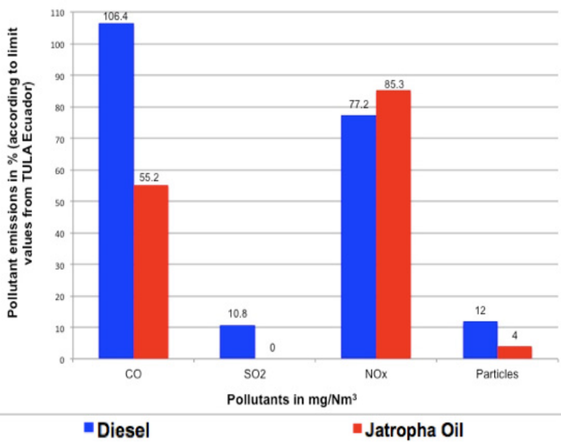

Figure 9: Emissions of Floreana engines with diesel and jatropha fuel

With the exception of a 5 % exceeding of the CO emission limit in diesel operation, all other emissions for jatropha and diesel operation clearly fulfilled the required local emission standard for Galapagos. Basically, CO and particle emissions of jatropha are half of the emission in diesel mode (particulate emissions have been calculated by the National Technical Institute). Emission for sulphur is zero because there is practically almost no sulphur in jatropha oil. Due to a faster combustion, the NOx emissions of jatropha oil is about 10 % higher than with diesel fuel but still below the required limit for NOx.The fully developed and tested pilot project Floreana will be scaled up in 2016 from Siemens AG at the more than 10 times bigger Galapagos Island Isabela. Fig. 10 presents the planning concept for hybrid system on Isabela Island [18].

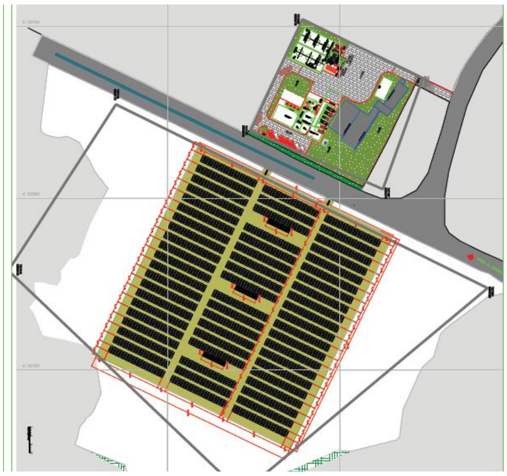

Figure 10: Isabela hybrid system with photovoltaic, battery and flex-fuel engines

The flex fuel engine technology on Galapagos Island Floreana and the 2nd generation jatropha oil fuel production in this respect is a technically evolutionary model not only for the other Galapagos Islands but for any other island or agricultural area in the world to achieve a 100 % sustainable and renewable energy supply. The Galapagos Islands with their long history of evolution, however, seem to be one of the best places in the world to create blue prints of revolutionary technologies with the help of biofuels which are necessary for the transition from the terminated fossil age to an infinite renewable energy era.

3.3 2nd Generation Pure Plant Oil Engines in Tractors

The immediate use of pure plant oil in agriculture is one of the most obvious applications, since economic and ecological efficiency would be maximised with simultaneous cultivation, production and use of plant oil. Additionally, typical agricultural work and transport premises require a high power demand and energy efficiency which are served up to 100 % with diesel engines and do not leave much vision for electro mobility.

Figure 11: John Deere flex-fuel tractor at Poznan Climate Conference in 2009

Technical changes to John Deere tractor shown in Fig. 11 concerning combustion method, injection technology, fuel circuits and other engine parameters are either achieved mechanically or via the engines' software.
Fig. 12 and 13 illustrate one example of an adapted software design. The first figure shows the original software architecture of the turbocharger pressure and the second figure is the adapted design for 2nd generation plant oil fuel [19].

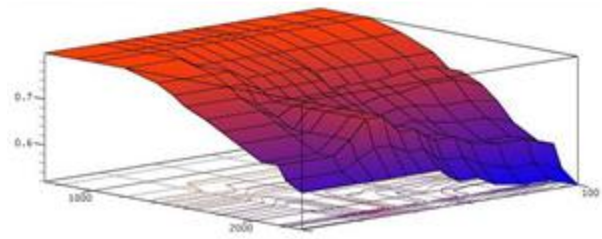

Figure 12: Software map of turbocharger pressure original

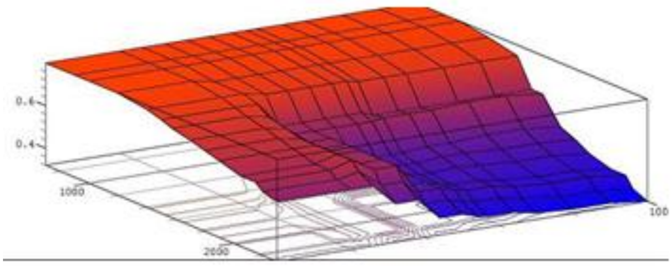

Figure 13: Software map of turbocharger adapted by Dts/VWP

For the whole electronical modifications of a flex-fuel engine more than 20 engine operation tables need a different and specific software mapping. During a R&D and demonstration phase over three years with 16 John Deere tractors in four European countries, the emission classes TIER 3A, 3B, 4 interim have been developed and tested. The TIER 3A emission results of diesel and four other plant oils measured in conformity of 97/68 EC are displayed in the following Fig. 14.

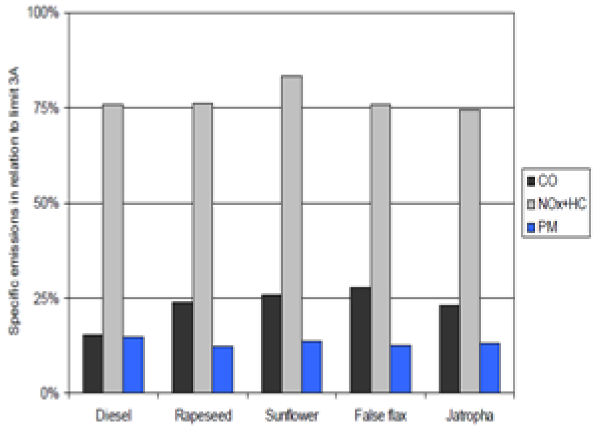

Figure 14: Limited emission results of stage 3A common-rail engine with diesel and different plant oil fuels [20]

All limited CO, NOx/HC and Particulate emissions comply with Tier 3A level which will be valid in many countries of Latin America, Africa and Asia in the next future. For agricultural mobility in these areas, a tested and reliable all-fuel tractor and engine generation already exist which can be operated with various 2nd generation plant oils.

3.4 2nd Generation Pure Plant Oil Engines in Rural Transportation

Agricultural areas around the world which are hard to provide with fossil fuel mostly are ideal areas for growing plant oil. Therefore, VWP-Gruber and partners decided to develop and offer to these areas a common-rail engine technology for light transportation vehicles (pick-ups) which can use 100 % domestic 2nd generation plant oil as well as diesel, biodiesel or blends of all fuel types [21]. The R&D project started with an investigation of the dynamic injector and spray behaviour in a high pressure chamber using different plant oils with varying viscosities [22]. Then it focused on the most sold and most modern 1.6 l and 2.0 l VW common-rail engines with sophisticated exhaust gas emission treatment systems. In Fig. 15 a pick-up VW Amarok with 2.0 l common-rail engine is performing an emission test at a test stand for dynamic emission testing.

Figure 15: Emission testing of Amarok 2.0 l at exhaust roller dynamometer test bench

To prepare for the international market the functionality of the VW common-rail engines and emissions have been tested with diesel and several plant oils. The Amarok warm-start emission tests have been performed with diesel, jatropha oil and rapeseed oil complying with 692/2008/EG city and autobahn test cycle.

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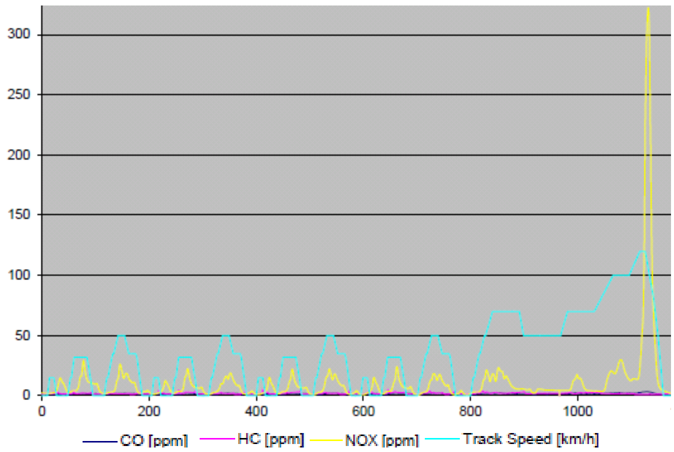

Figure 16: Jatropha oil emission test with test cycle 692/2008/EG

Fig. 16 presents the dynamically measured CO, HC and NOx emissions with jatropha oil during the 1,200 sec. lasting 692/2008/EG test cycle at a speed between 0 and 120 km/h. All emissions for NOx, CO, HC and PM stayed within the 100 % limit. At a stationary test bench at the OTH Regensburg basic emission measurements with diesel and 2nd generation plant oils have been conducted with a 4-cyl. 1.6 l common-rail engine. The following four figures Fig. 17 to 20 illustrate the break specific fuel consumption as well as the emission levels of CO, HC and PM with varying NOx-emissions due to the variation of exhaust gas recirculation. [23].

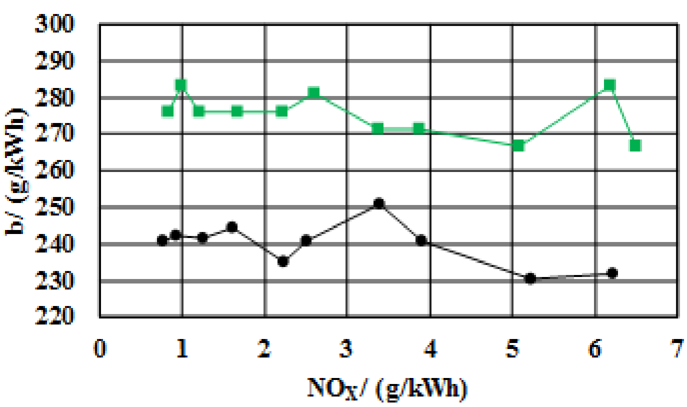

Figure 17: Comparison of the break specific fuel consumption between diesel and jatropha at a 4-cyl. 1.6 l common-rail engine

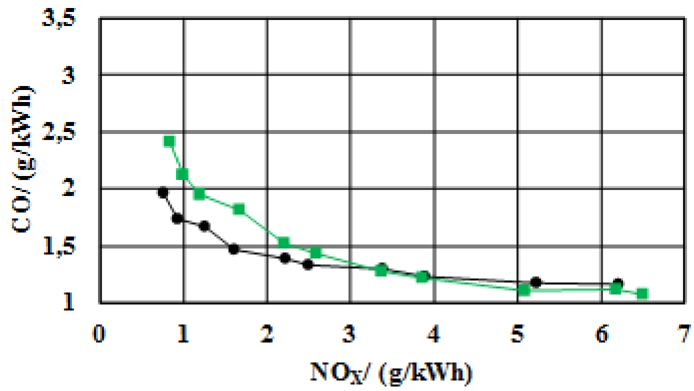

Figure 18: CO emission comparison between diesel and jatropha at a 4-cyl. 1.6 l common-rail engine

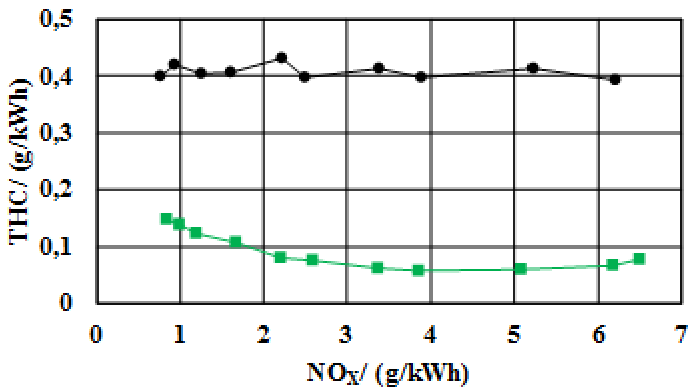

Figure 19: HC emission comparison between diesel and jatropha at a 4-cyl. 1.6 l common-rail engine

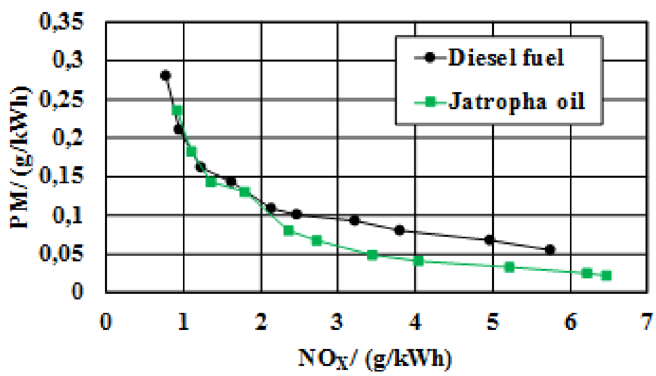

Figure 20: PM emission comparison between diesel and jatropha at a 4-cyl. 1.6 l common-rail engine

The engine was operated with an injection pattern of two pre-injections, one main injection and one post-injection with a constant power of 12.5 kW at 1500 rpm and 80 Nm. By variations of the exhaust gas recirculation (EGR) and a complementary continuous shifting of the complete injection pattern to earlier crank angle levels it was possible together with slight adaptations of the main injection fuel rate to always keep the centre of combustion mass at 15° crank angle.With such a defined operation mode, a comparison of emission levels between jatropha and diesel fuel at varying EGR rates indicates a general disadvantage of jatropha respective to the break specific fuel consumption (Fig. 17). This phenomenon could easily be explained by the decreased heating value of jatropha compared to diesel fuel.

Figure 18 illustrates higher CO emissions with jatropha by increasing the EGR rate. The reason for this emission pattern is the changed mixture formation with jatropha compared to diesel fuel due the difference in physical properties such as surface tension, viscosity and density. This effect is stronger at higher EGR rates, reinforced by the increased lack of oxygen. In figure 19, the HC emissions of jatropha show a lower level than diesel over the complete EGR variation. The higher oxygen content of jatropha (11%) instead of Diesel (0%) accelerates the combustion and decreases the probability of flame extinguishing, which leads to lower HC levels.

The PM emissions are lower due to the higher oxygen content of jatropha which leads to a better soot oxidation. At higher EGR rates the PM emissions of diesel and jatropha are equal (Fig. 20).The NOx emissions with jatropha are slightly higher at the point without EGR, which is illustrated in the figures 17 to 20. This phenomenon is also caused by the high oxygen content of jatropha which leads to a shorter combustion duration and higher combustion peak temperatures. Functionality and emission test programs at a one cyl. high pressure chamber, a stationary test bench and an exhaust roller dynamometer test bench finished the R&D phase. A practical summer/winter- and short/long distance field test was conducted with an Audi A4, A6, Q5, and a VW Amarok to proof the flex fuel functionality of the Volkswagen 2.0 l common rail engine for diesel and different 2^{nd} generation plant oils. For rape seed oil, jatropha oil, diesel and plant oil/diesel blends all practical tests over two years finally showed a similar behaviour in functionality, consumption and emission like original benchmark vehicle from Volkswagen/Audi[24].

IV. Conclusion

The 21 Century will be the century of decarbonisation and transition from finite fossil energies to renewable energies. The “Zero Fossil Fuel for Galapagos Islands” initiative might be a blueprint for a technological evolution to change world’s standards for electricity and mobility. Sustainable bio fuels will be necessary for electricity production and heavy or long distance transport. As alcohol or biogas can fuel gasoline engines pure plant oil is a promising option for the diesel engine [25]. Agricultural areas in the world very often are off grid areas with a difficult logistic and reachability and often comparatively poor. Therefore centralized, energy consuming and expensive technically sophisticated industrialized bio fuel strategies like hydrogen, hydro cracking, drop in fuels, or 3^{rd} generation fuels mostly are not suitable for agricultural energy purposes. Sustainable 2^{nd} generation pure plant oils in DIN 51623 fuel quality from decentralized oil mills are a future fuel for rural areas to provide the demand for transport and balancing power within a 100% renewable energy hybrid system.

In combination with advanced flex fuel engines 2^{nd} generation plant oils fulfil latest emission requirements and potentially offer the most comprehensive ecological, economic and social benefits of all bio fuels particularly for agricultural engines [26]. Especially in remote areas with often limited access to engine fuels, multi fuel capacity of agricultural engines gives more options and variances for a multiple and safe fuel supply.So, for the most pestering world problems such as climate change, decreasing resources of fossil energies and the need of providing food, feed and fuel to an increasing world population at the same time to affordable prices, 2^{nd} generation pure plant oils especially for the agricultural sector is a conclusive answer.Together with advanced flex fuel engines a change from a centralized finite fossil fuel energy era to a decentralized and infinite renewable energy concept is technically immediately practicable and economically and ecologically feasible.

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Development of fast running, small volume common-rail-engines for pure plant oil and development and testing of 2^{nd} generation plant oils (jatropha, pongamia) at vehicles and test stands (ZIM KF2784402GB2): Federal Ministry for Economic Affairs and Energy, 2012-2015

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