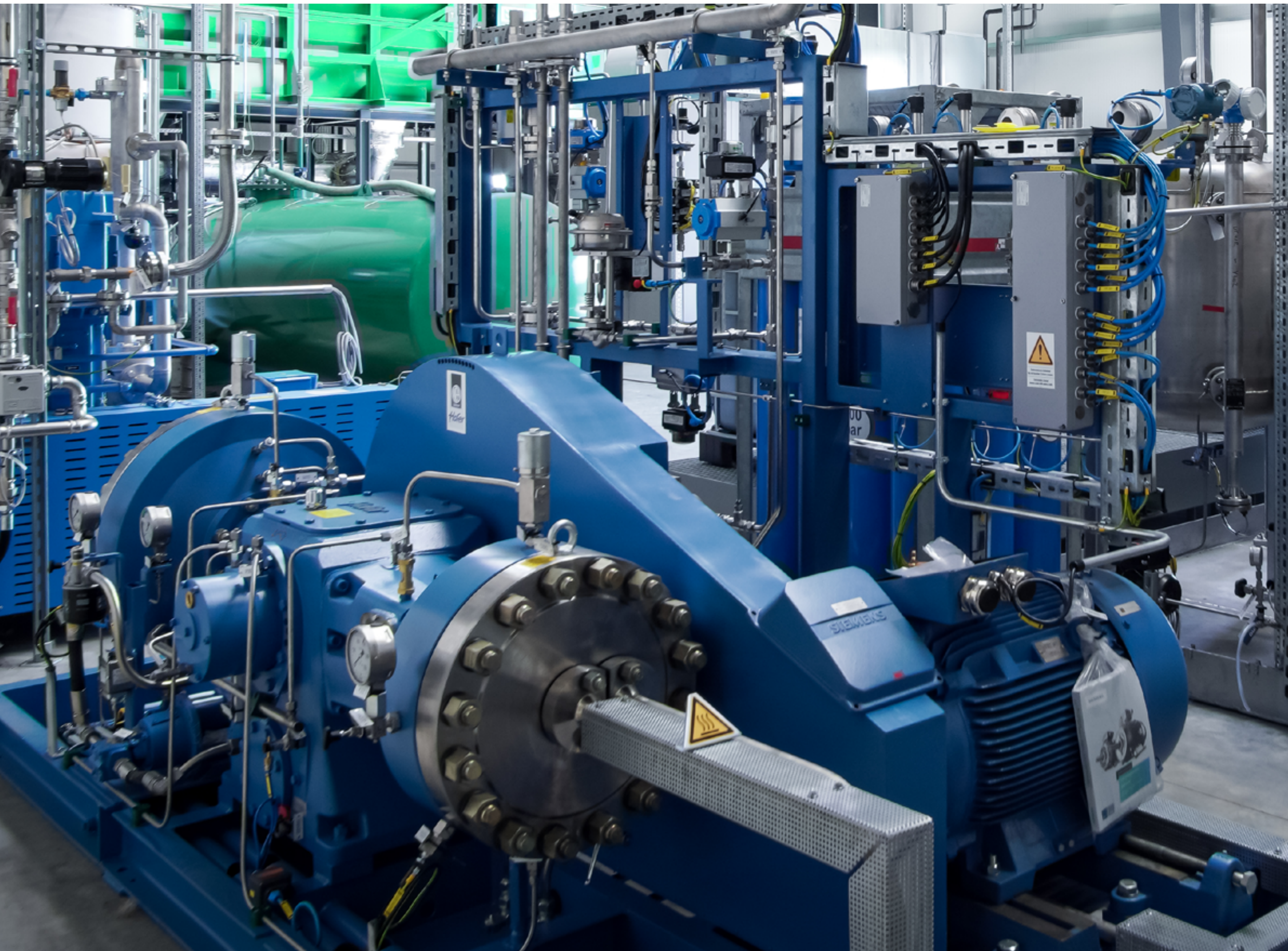
TO-SYN-FUEL PROJECT

Turning sewage sludge into fuels and hydrogen

The Demonstration of Waste Biomass to Synthetic Fuels and Green Hydrogen



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Finding online information about TO-SYN-FUEL project

Project website
www.tosynfuel.eu

Cordis webpages
https://cordis.europa.eu/project/id/745749

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Credit: Fraunhofer UMSICHT

Disclaimer
This publication is about TO-SYN-FUEL project. TO-SYN-FUEL is a Horizon 2020-funded project coordinated by Fraunhofer Institute for Environmental, Safety, and Energy Technology (Fraunhofer UMSICHT) in Germany. The project began in May 2017 with a financial volume of 14.5-million-euro funding. It ends in September 2022 after more than 5 successful years, demonstrating a sustainable process that can transform waste biomass, such as dried sewage sludge into high-quality renewable liquid fuels and hydrogen.

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Contents

Foreword

The European Green Deal is a top priority for climate, energy and mobility. The target is for Europe to become climate-neutral by 2050, protecting humans, animals and ecosystems, but also creating economic growth across all demographics. All these measures are important for the support of biofuels, bioenergy and renewable fuels, under sustainable conditions and with sustainable feedstocks. In addition, the Fit for 55 package was adopted in the second part of 2021 by the European Commission to implement the 2030 Climate target plan with the 55% greenhouse gas emissions reduction.

The TO-SYN-FUEL project, that ends in September 2022 after more than 5 successful years, is demonstrating a sustainable process that can transform waste biomass, such as dried sewage sludge into high-quality renewable liquid fuels and hydrogen H_2.

TO-SYN-FUEL integrates three different technologies in a new process to convert a wide range of residual and waste biomass: the pyrolysis-based Thermo-Catalytic Reforming (TCR, Figure 1), hydrodeoxygenation (HDO), and pressure swing adsorption (PSA) will successfully achieve the project's three key objectives:

1) the optimisation of the technologies involved,
2) their integration into a pilot plant,
3) the end use demonstration of diesel-equivalent fuel for transport.

As TCR can process a series of poor-quality waste organic feedstocks such as sewage sludge, paper industry residues, the organic fraction of municipal solid waste, anaerobic digestate, this flexibility is important for enabling the process to be adapted and integrated into a wide range of different scenarios.

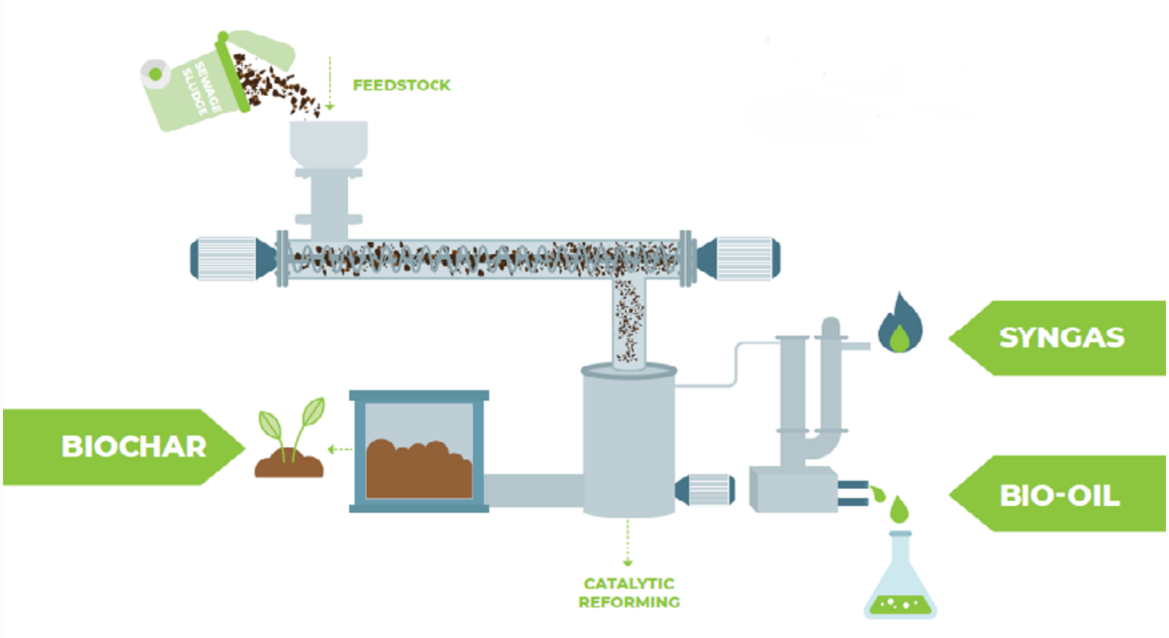


Figure 1. Thermo-Catalytic Reforming TCR: A Platform Technology to use residues and to produce sustainable and storable energy carriers.
Credit: Fraunhofer UMSICHT.

Acknowledgements

TO-SYN-FUEL is a Horizon 2020-funded project coordinated by Fraunhofer Institute for Environmental, Safety, and Energy Technology (Fraunhofer UMSICHT) in Germany that is seeking to build-up, operate and demonstrate the production of synthetic fuels and green hydrogen from waste biomass.
The project began in May 2017 and will run for a period of 65 months, and it has a financial volume of 14.5-million-euro funding. As part of Horizon 2020's new research and innovation programme, it is assisting in the long-term goal of bringing innovative biofuels from sustainable raw materials to the market.

A new integrated process combining Thermo-Catalytic Reforming (TCR), with hydrogen separation through pressure swing adsorption (PSA), and hydrodeoxygenation (HDO) produces a fully equivalent gasoline and diesel substitute. This technology promoted by TO-SYN-FUEL will contribute to decarbonize the transport sector.

The project consortium comprises of key industrial stakeholders with the knowledge and expertise to develop and implement a full commercial scale technology.
The key industrial partners consist of stakeholders with expertise ranging from across the whole value chain and include engineering providers as Verfahrenstechnik Schwedt, Martech, Engie Services Netherlands and HyGear Technology and Services, and fuel off takers as Eni.

Academia is also heavily involved, with collaborators including the University of Bologna in Italy (full life cycle analysis, LCA, of the process) and the University of Birmingham in the UK (feedstock characterisation, intermediate and final product properties). Specific tasks supporting the technology and knowledge transfer are in charge of LEITAT (social sustainability), ETA-Florence and WRG Europe, project partners with a valuable expertise in those fields.
Fraunhofer UMSICHT has developed a technology called Thermo-Catalytic Reforming (TCR), which it hopes will have a significant impact on addressing sustainable energy, economic, social and environmental needs.

"In this project we want to produce advanced biofuels from waste, which in this particular case will be sewage sludge. We have built-up the plant and we demonstrate the technology in operation. By the end of the project, we want to have a business case for sustainable green fuels in order to support the targets of the European Commission.", Dr -Ing. Robert Daschner from Fraunhofer Institute for Environmental, Safety, and Energy Technology (UMSICHT), co-ordinator of TO-SYN-FUEL project (The Demonstration of Waste Biomass to Synthetic Fuels and Green Hydrogen).

This publication was prepared by all project partners and reports main activities and developments of the project that have occurred up to September 2022, as described in detail in all published project deliverables.

Acronyms

APF: Assigned Protection Factors
CAPEX: CAPital EXpenditur
CHP: Cogeneration of Heat and Power
CLP: Classification, Labelling and Packaging
DM: Dry Matter
DNELs: Derived No-Effect Levels
ECHA: European Chemicals Agency
ECETOC: European Centre for Ecotoxicology and Toxicology of Chemicals
EN: Europäische Norm (European Norm)
ES: Exposure Scenario
ESP: ElectroStatic Precipitator
EU: European Union
EUBCE: European Biomass Conference & Exhibition
FU: Functional Unit
GHG: GreenHouse Gas
GWP: Global Warming Potential
HBO: Hydrotreated Bio-Oil
HDO: HydroDeOxygenation
HGC: Hot Gas Cleaning
HHV: Higher Heating Value
ICP: Inductively Coupled Plasma
KPI: Key Performance Indicator
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LHV: Lower Heating Value
OC: Operational Conditions
OFMSW: Organic Fraction of Municipal Solid Waste
PSA: Pressure Swing Adsorption
RCR: Risk Characterization Ratio
REACH: Registration, Evaluation, Authorisation and restriction of Chemicals
RED: Renewable Energy Directive
RMM: Risk Management Measures
rpm: revolution per minute
TAN: Total Acid Number
TCR®: Thermo-Catalytic Reforming (or TCR)

Introduction

TO-SYN-FUEL demonstrates a new integrated process combining Thermo-Catalytic Reforming (TCR), with hydrogen separation through pressure swing adsorption (PSA), and hydro-deoxygenation (HDO), to produce a fully equivalent gasoline and diesel substitute (compliant with EN228 and EN590 European Standards) and green hydrogen for use in transport (Figure 2).
The primary ambition of this project was to demonstrate and validate the technical and economic viability of the integrated TCR/PSA/HDO technology approaches, together with their environmental and social sustainability, as well as the cost-competitiveness, at near commercial scale through the construction of a demonstrator that will also serve as an exemplar to facilitate rapid commercial uptake.

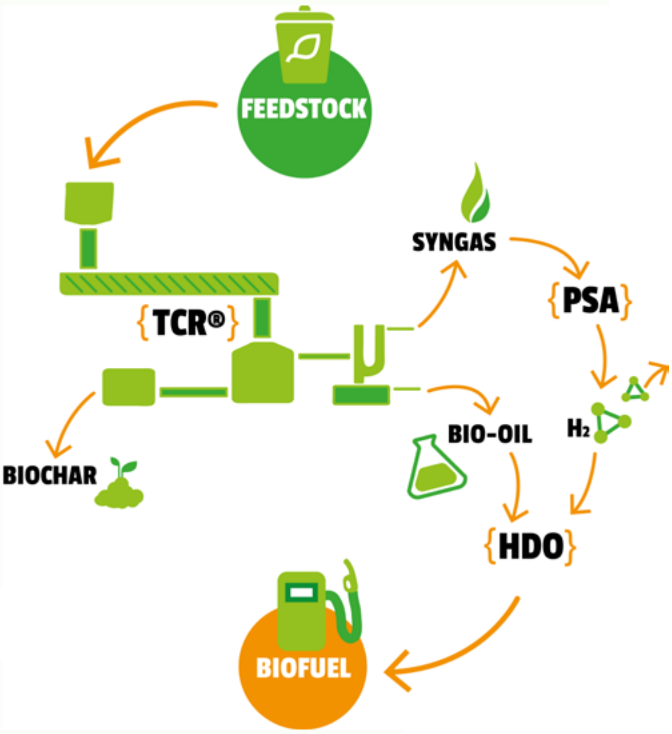


Figure 2. TO-SYN-FUEL process scheme.
Credit: TO-SYN-FUEL project.

Credit: Fraunhofer UMSICHT.

This validates a comprehensive exploitation business plan, building on already established end user interest – thus gaining an advantage to market with commercial exploitation of the technology as the next step of development. The scale up of such plants up to a capacity of three tonnes per hour and more for the installation throughout Europe would be the driver to produce thousands of tons of green fuel per year from organic wastes with greenhouse gas (GHG).
The TO-SYN-FUEL pilot plant built in Markt Hohenburg, district of Amberg-Sulzbach (Germany) can treat up to 500 kg/h of dried sewage sludge, which yields up to 50 litres/hour of biofuel.

Project timeline

2016

The European Commission released its proposal for the RED II, the Renewable Energy Directive for the post 2020 period, in December.

2017

Fraunhofer UMSICHT, To-Syn-Fuel project coordinator, hosted the kick-off meeting in Sulzbach-Rosenberg, Germany, in May.

2018

Fraunhofer UMSICHT presented the project during the 26th European Biomass Conference & Exhibition (EUBCE), in Copenhagen in May.

The first TCR® research & development plant processed dried sewage sludge and achieved an important milestone with a successful > 50 hours test run in May.

Project partners visited a sewage sludge treatment plant at a site in Hohenburg, Germany, in June. This plant locally dries and produces sewage sludge feedstock.

The starting signal for the construction of the To-Syn-Fuel plant, a pre-commercial demonstrator for the production of advanced biofuels from sewage sludge, was given during the ground-breaking ceremony in Markt Hohenburg Industrial Park in November.

2020

At the beginning of the year, the pilot plant hall for the To-Syn-Fuel demonstrator was completed and the first components were on site.

2021

The demonstrator plant was in operation in the second part of the year to produce biocrude oil. TCR® is combined with pressure swing adsorption (PSA) and hydrodeoxygenation (HDO) technologies in an integrated plant.

2022

To-Syn-Fuel project conference and plant Demo Day were held virtually by EUBCE 2022 in May.

A car, fuelled with To-Syn-Fuel diesel, will stop at key locations around Europe in September to promote the technology and the importance of biofuels in the clean energy solutions mix for greener transport.

Upon successful demonstration of the first integrated TCR®/PSA/HDO plant, there are plans in place for the future role of the technology.

1 Feedstock

The demonstration plant in Hohenburg is tested with sewage sludge from the local drying company E&T Aichaberg GmbH & Co. Trocknungs KG. The quantity of sewage sludge currently delivered from several wastewater treatment plants in the region to the dryer is about 40.000 t/a at 25% dry matter (DM) content. This means, that four times the demonstration plant with a throughput of 500 kg/h dried sewage sludge would fit. Close to this location a further drying company is based in the same county with a capacity of about 50.000 t/a of sewage sludge at 25% DM (ARGE UTE / GP Ingenieure GmbH 2017).

The organic fraction of municipal solid waste (OFMSW) and sewage sludge represent a large amount of the biodegradable waste generated in the EU. The most recent estimates, reported to the Commission by the Member States, suggest that about 100 million tonnes of biowaste from municipal solid waste and sewage sludge dry matter are produced in the EU every year.

Sewage sludge evolves from the treatment of wastewater to produce a 'sludge cake'. It is a highly abundant waste with a yearly production potential of approximately 90 kg per inhabitant per year (wet basis). Germany currently produces 1.8 million tonnes per year of sewage sludge on a dry basis.

Similar to anaerobic digestion residues, there are increasing legislative demands imposed on the disposal of sewage sludge by landfill, land spreading and incineration.

In Italy and according to Eurostat data, landfill remains the major disposal route for sewage sludge, followed by land spreading. In countries such as Germany or Netherlands, incineration is applied to a higher degree. Considering Europe consists of 27 countries and UK, the most commonly used disposal method in 2012 was land spreading, followed by incineration and then composting and landfill.

Ultimately, the choice of the most appropriate management and treatment process for sewage sludge is, of course, deeply related to the local conditions. It is known that landfill disposal of sludge affects the leachate production and the CO_2 emissions directly to the air. Therefore, the main methods of sewage sludge management in the EU remains agricultural use and incineration.

The total quantity of sewage sludge in Europe is about 9.2-9.5 Mio. t/a (DM) (Roskosch und Heidecke 2018; Statista 2021). The current use or respectively disposal of sewage sludge in Europe is the following: 47% agriculture, 10% landfill, 26% incineration, 13% composting and recultivation (EUWID 2017). The direct use in agriculture and the use in composting and cultivation are controversial options, because of the content of heavy metals, organic pollutants as well as bacteria and worm eggs (Roskosch und Heidecke 2018). If sewage sludge is disposed on landfills the contained energy as well as phosphorus are lost. Only one fourth of the European sewage sludge is treated by incineration to destroy organic pollutants as well as biological threats. Therefore, it is given a high potential feedstock for the TCR process.

However, the distribution of the sewage sludge to the different utilization pathways varies in the European countries. In Germany and the Netherlands the predominant treatment is the incineration, while in UK and Spain most of the sludge is applied in agriculture. These countries are rather suitable for the installation of treatment capacities. The sewage sludge quantities in both countries are in each case about 1.1 Mio. t/a (DM) (Statista 2021).

Characterisation of sewage sludge

All dried sewage sludge feedstocks as received in TO-SYN-FUEL project were characterised with a maximum error of (+- 3%) are assumed to give accurate representation of the feedstocks processed via the TCR post pre-treatment at Hohenburg.

Samples were sent on a regular basis for analytical characterisation. Sewage sludge consisted of granular material as shown by Figure 3. Before receiving the sewage sludge, the feedstock was first dried in Hohenburg by the company E&T Aichaberg who receives wet sludge from regional municipalities. E&T Aichaberg uses a state-of-the-art belt drying technology to dry the sludge to moisture content below 10 wt%. The heat required for drying the sludge is obtained from off heat produced by an onsite wood gasification unit, using wood pellets. In total, they dry approximately 18,000 tonnes per year of dewatered sludge per line with two operational lines and drying temperature below 100 °C.

No further pre-treatment is carried out before TCR conversion at Hohenburg, and no further pre-treatment was carried out before analytical characterisation as to give an accurate representation of the feedstock characteristics upon entry to the TCR.

The ultimate analysis shows that Carbon and Hydrogen yields in the sewage sludge were on average 29.9 and 4.5 wt% respectively, the presence of N and S elements were also detected within the feedstock. The average oxygen content of the feedstock was 21.5 wt%. The proximate analysis results indicates that the drying pre-treatment was effective in bringing the moisture content of the sludge down to below 5 wt% on average.
The sewage sludge contains a relatively high amount of ash (38.6 wt% avg) and low fixed carbon (5.8 wt% avg) which corresponds to a calculated gross calorific value HHV of approximately 12.8 MJ/kg which is approximately half that anthracitic coal. In terms of atomic ratios the sludge is also approximately 10 orders of magnitude grater that that of anthracitic coal. The metal ICP analysis of the feedstock shows the main metals detected within the sewage sludge was calcium, iron, phosphorus, aluminium, magnesium, potassium, and silicon. All of these metals with the exception of silicon are believed to play an important role in the catalytic function of sewage sludge within the post reformer. Samples were also analysed for heavy metal detection and compared with the EU limits for use as soil improvers. Some heavy metals were detected although most fell within the EU limits for soil improvers such as Chromium and Nickle. No Cadmium, Mercury or Lead was detected in the samples. Zinc and Copper fell outside the limits.

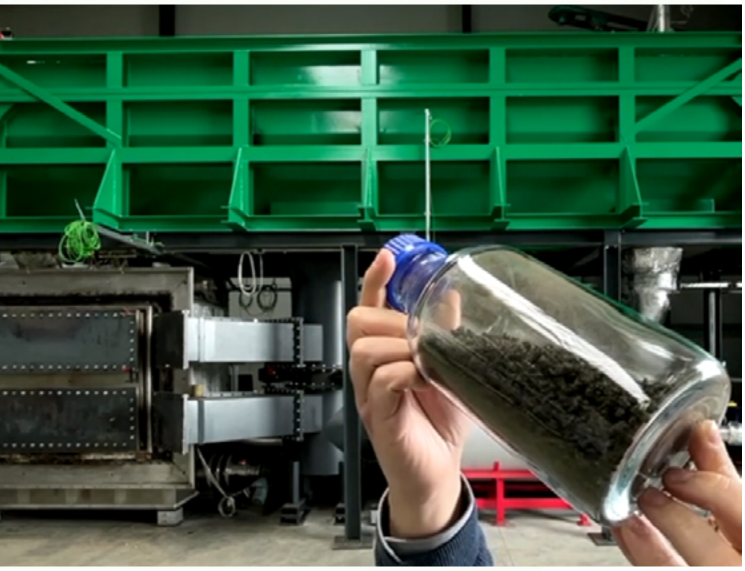


Figure 3: Dried sewage sludge feedstock.
Credit: TO-SYN-FUEL project.

Credit: TO-SYN-FUEL project.

2 Technology

The objective of the TO-SYN-FUEL project is to demonstrate the feasibility of a new integrated process combining Thermo-Catalytic Reforming (TCR), with hydrogen separation through pressure swing adsorption (PSA), and hydrotreatment (HDO), to produce an equivalent gasoline and diesel substitute and green hydrogen for use in transport.

Fraunhofer UMSICHT has developed a technology called Thermo-Catalytic Reforming (TCR), which it hopes will have a significant impact on addressing sustainable energy, economic, social and environmental needs.
The technology produces renewable liquid fuels from waste biomass, converting residual biomass into three main products: H_2-rich synthesis gas, biochar and liquid bio-oil. Using high-pressure hydro-deoxygenation (HDO) in small-scale refining units that operate in multiple decentralised locations, the distillation creates a diesel or petrol equivalent that can then be used directly in internal combustion engines. The main goal of TO-SYN-FUEL is to demonstrate and validate the technical and economic viability of TCR in combination with PSA and HDO, as well as its environmental and social sustainability.
To do this, the researchers are combining TCR, HDO and pressure swing absorption (PSA) with respective environmental and social sustainability mapping in one plant (Figure 4).

Considering the significant demand for processes that can produce sustainable advanced biofuels efficiently and cost competitively in smaller decentralised units, this integrated approach presents many advantages in terms of flexibility of scale and delocalisation at regional and local level, flexibility of feedstock, quality and reproducibility of products, and competitively low costs (capital and running).

Figure 4: Pilot plant for the TO-SYN-FUEL project in Markt Hohenburg, district of Amberg-Sulzbach.
Credit: Fraunhofer UMSICHT.

Main section

Figure 5 shows the overall demonstrator unit located in Hohenburg. On the right-hand side of Figure 5, the feedstock is inserted via a screw conveyer system into the TCR auger reactor system. The feedstock is processed in the TCR auger reactor and the subsequent post reformer.
The produced vapour phase is entering the product gas train (middle part of Figure 5). After leaving the product gas train, the cold TCR-gas is fed into the PSA-unit. The produced TCR-crude oil is upgraded in the hydrotreatment unit. For this upgrade the hydrogen from the PSA unit is used.

Thermo-Catalytic Reforming (TCR) and post reformer

The TCR core components, including auger reactor (green component), post reformer unit (bottom left) and the heating unit are shown in Figure 5. The heating system is fuelled by propane and can also be operated with TCR gas and TCR tail gas from the PSA unit. The combustion chamber provides flue gas at temperatures up to 1,000 °C.

The auger reactor is the first reactor stage of the TCR-500 and has a capacity of 500 kg per hour of feedstock. The feedstock is converted into a char and a vapour phase at temperatures of approx.
450 °C. It is a screw reactor with a length of approx. 8.6 m and operated at low rotational speed of 2-9 rpm.
Both, the char and the vapours are further processed in the post reformer unit.

This is the second reactor stage of TCR-500.
With a volume of approx. 1.5 m³ the catalytic reforming takes place at temperature between 500 and 700 °C.
This is the most important step for the optimisation of product quality and the increase of H_2 content in the syngas up to 45 Vol.%. Additionally, acids (TAN) are reduced and long hydrocarbon chains are cracked. No external catalyst is needed therefore.

Product gas train and syngas compressor

The next process step is the product gas train, where the produced TCR vapours are cleaned and condensed.
The hot gas cleaning system (HGC) consists of two cleaning steps. The first cleaning step is a multi-cyclone that cleans rough particles from the gas coming from the post reformer. The second step of the HGC-system is the hot gas filter. The filters are made of ceramic-fibre bag filters that can be cleaned by a nitrogen jet stream.
Downstream the filters, the condensation stage of the product gas train is installed. It is built of a shell and tube cooler to condensate the liquid phase from the permanent gas. The liquid phase is collected in a reservoir and pumped into a subsequent gravimetrical separator, where the TCR-oil is separated for further processing.
Final step of the product gas train is the permanent-gas cleaning step. An electrostatic precipitator (ESP) cleans the gas from aerosols that can be formed during the condensation step. Afterwards the ammonia contend in the gas is removed by a scrubber.

Figure 5: Complete process chain of TO-SYN-FUEL-demonstrator.
Credit: Fraunhofer UMSICHT.

The product gas coming from the TCR-500 system has to be compressed for the operation of the PSA system. This is done by a two-stage piston compressor from approx. ambient conditions up to 12 bar. The operational flow rate of the gas is approx. 100 Nm³/h.

Pressure swing adsorption

The PSA receives the TCR gas phase and the hydrogen recycle stream of the HDO unit. The TCR gas is compressed up to 12 bar by the syngas compressor. The combined gas stream enters the 4-vessel-PSA, shown in Figure 6, in which the hydrogen is separated from the other species (CO, CO_2, CH_4, N_2), called the offgas. The hydrogen is sent to the hydrogen compressor and -storage and the offgas is fed to the CHP engine. The PSA container (Figure 6) contains a vacuum pump to increase the efficiency of the system. The PSA is controlled based on the purity of the hydrogen. The purity can be controlled to a desired CO concentration in the hydrogen measured by an onboard infra-red analyser. The inlet- and offgas stream are also analysed to measure the mass-balance of the PSA. The PSA can be operated remotely and has its own safety equipment and controls. It is constructed in a container for easy transportation and installation.

Figure 6: PSA unit.
Credit: Fraunhofer UMSICHT.

Hydrogen compressor

The hydrogen (H_2) coming from the H_2 storage tank or directly from the PSA has to be compressed from approximately 10 bar (PSA) / 50 bar (H_2 storage tank) up to 140 bar (Figure 7). The operational flow rate of the H_2 is approx. 180 Nm³/h.

Figure 7: H_2 compressor.
Credit: Fraunhofer UMSICHT.

Hydrotreatment unit

The hydrotreatment unit (HDO) of the TO-SYN-FUEL project is designed to process up to 35 liters of TCR-oil per hour. All components including piping and wiring are completed.

In addition, the automation set up took place and the unit is ready for commissioning. First pre-commissioning test with hydrogen bundles has been done.

Reactors catalyst change mechanism was successfully tested. All reactors were lifted individually from the steel construction. The process has been optimized to facilitate the dismantling of the reactors and reduce the time required for this changing process.

3 Products and end uses

Liquid bio-oil from TCR can be upgraded to green fuels capable of being used directly in automotive internal combustion engines without modification, as they fulfil EN fuel standards.
In this project, the operational capacity of TCR is designed for up to 500 kg per hour of sewage sludge at a water content of 5-15%. The main purpose of this unit is the long-term operation of a pre-commercial demonstrator. This is the final step of development before the technology can move to full commercial scale. This integrated unit will be operated from 2021 for up to 5,000 hours of operation and for the production of more than 50,000 litres of biocrude oil.

The development process of this novel technology has shown a high potential in the application and utilization of biomass and residues – a decentralised application for sustainable energy has been developed. The intermediate bioenergy carriers address application in existing infrastructure and consequently reduce the specific costs.
The development of the TCR-500 pre-commercial scale plant is the basis for the commercialization and market-roll-out of the technology.
The objective is to integrate the three key technologies into one single process. The bio-oil feedstock from the TCR will be fed with hydrogen from the PSA unit into a fixed bed reactor system. There, the reactions occurring over the catalysts will involve the removal of heteroatoms of the bio-oil such as sulphur, nitrogen and oxygen, and therefore an increase in the quality of the oil. This process will run with a surplus of hydrogen.
With respect to the economic efficiency and the environment, this excess will be recycled through the PSA unit.
By integrating HDO processes, the resulting bio-oil can be upgraded to green fuels that are ready to be used directly in internal combustion engines.
TO-SYN-FUEL final products are therefore renewable liquid fuels from waste biomass ready to replace fossil fuels in compliance with EU standards for gasoline and diesel EN228 and EN590, which have already been proven viable on a pilot scale.
Moreover, due to this process, the generated green H_2 will create a new value chain including hydrogen-fuelled transport.
The main objective of the TO-SYN-FUEL process is to create TCR bio-oil from sewage sludge as feedstock, then upgrade it into HDO bio-oil and to separate from the synthesis gas the produced H_2, creating a new value chain.

Liquid TCR-oil

The liquid bio-oil being produced by TCR is thermally stable (Figure 8), has low viscosity and polarity, low water and oxygen content and a high heating value (LHV: ≈35 MJ/kg). Being a high-quality oil and engine-ready, it therefore represents an excellent precursor for hydrotreatment.

Synthesis gas

Concerning Syngas deriving from the TCR process, it is an engine-ready gas with a heating value of ≈12-18 MJ/m³ (HHV). It contains high hydrogen content for hydrogen separation through Pressure Swing Adsorption.

H^2	38 ± 3 v/v%
CO	8 ± 2 v/v%
CO_2	30 ± 3 v/v%
CH_4	14 ± 2 v/v%
CxHy	3 ± 1 v/v%

Table I: Main features of synthetic gas deriving from dried sewage sludge thanks of TCR.

Hydrotreated TCR bio-oil

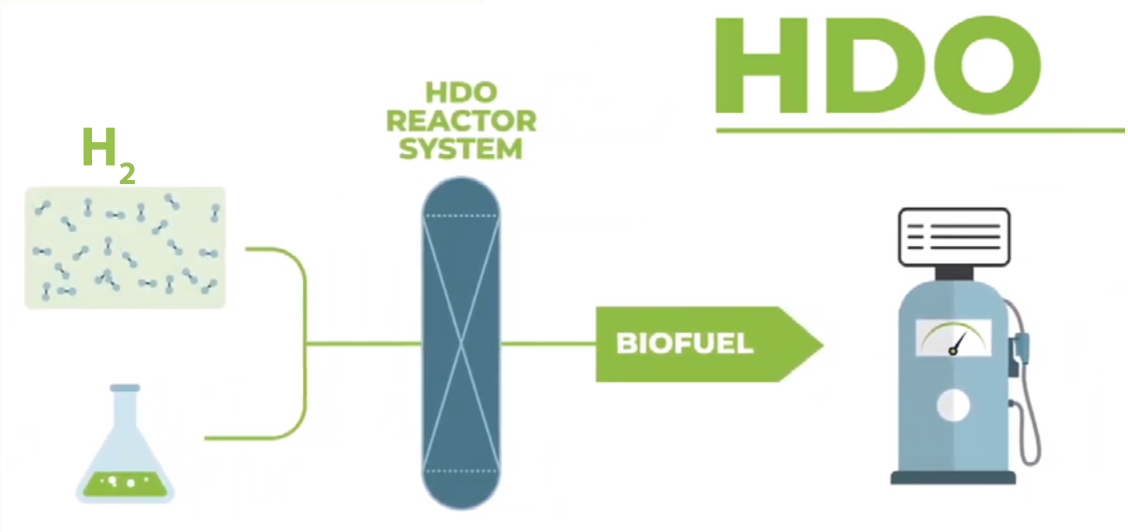
During the hydrotreatment process, which requires a thermally stable oil as it is carried out at a temperature of around 260-400 °C and up to 200 bar pressure, the TCR-oil is upgraded by H_2. The resulting products are H_2S, H_2O, NH_3 and hydrotreated TCR bio-oil (HBO).
This new HBO oil (Figure 8) presents some differences in comparison with the crude TCR bio-oil. It has an LHV of 42.25 MJ/kg, a viscosity of 0.97 mm²/s, a density of 815 kg/m³, as well as a flash point < - 20 °C. This liquid results as a mixture of EN conforming diesel and gasoline.

Figure 8: Samples of TCR-oil from sewage sludge and upgraded TCR-oil.
Credit: TO-SYN-FUEL project.

Credit: Fraunhofer UMSICHT.

Biochar

In regard to the carbonisate from dried sewage sludge, it has a very low H and O content as well as an HHV of about ≈10.5 MJ/kg (LHV ≈9.5 MJ/kg).
The gasification of char, as one option of utilization, with subsequent phosphorous recovery, produces:
- Additional H_2, as the overall process produces more H_2 than that being required for Hydrodeoxygenation (HDO);
- Better phosphorous recovery conditions;
- Additional energy for process heat;
- A technically low-tar gasifier gas.



Credit: TO-SYN-FUEL project.

4 Environmental, social impact and chemical risk assessment

Environmental impact assessment

Life Cycle Assessment (LCA) is a method for analysing and evaluating environmental performance of products, processes or services throughout their entire life cycle and it is a crucial tool to direct new products and innovative processes towards sustainability. The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the Life Cycle Inventory (LCI) results.
"The Renewable Energy Directive (RED II) mandates that 32% of all energy usage in the EU, including at least 14% of all energy in road and rail transport fuels, be produced from renewable energy sources (RES) by 2030. REDII defines a series of sustainability and GHG emission criteria that bioliquids used in transport must comply with to be counted towards the overall 14% target and to be eligible for financial support by public authorities. Some of these criteria are the same as in the original RED, while others are new or reformulated. In particular, the RED II introduces sustainability for forestry feedstocks as well as GHG criteria for solid and gaseous biomass fuels.
Default GHG emission values and calculation rules are provided in Annex V (for liquid biofuels) and Annex VI (for solid and gaseous biomass for power and heat production) of the RED II. The Commission can revise and update the default values of GHG emissions when technological developments make it necessary. Economic operators have the option to either use default GHG intensity values provided in RED II or to calculate actual values for their pathway (2018/2001/EC)".

The biofuels produced by the TCR/PSA/HDO integrated system are analysed evaluating the following plant configurations:
- Demonstrator 500 kg/h
- Commercial 500 kg/h

In both cases, the TCR treating capacity is 500 kg/h of dried sewage sludge and the two configurations mainly differ in terms of overall efficiency of the integrated system, which is higher in the commercial one.
Three different scenarios of TCR/PSA/HDO integrated system have been modelled for each configuration, which differ in terms of additional thermal energy provided for sewage sludge drying, for a total of six scenarios:

1. TCR/PSA/HDO natural gas, where the additional thermal energy for drying is provided by natural gas. It could be considered the usual solution.

2. TCR/PSA/HDO wood gasification, where the additional thermal energy for drying is provided by wood gasification. This scenario represents the current state of the project since the demonstrator plant in Hohenburg is installed right next to a wood gasification sewage sludge drying plant.

3. TCR/PSA/HDO greenhouse, where the drying is provided by hybrid greenhouse. This technology can be considered as CO_2-neutral since it does not need fossil energy. Also, this scenario can represent existing cases where off-heat from industrial process is used for drying.

Every scenario has then been compared with conventional fuels, gasoline and diesel respectively, and evaluated according to the guidelines defined in the Annex V of the RED II. It states that GHG emission savings from the use of biofuels shall be at least 65% respect the fuel comparator when they are produced in installation starting operation from 1 January 2021.
The Global Warming Potential (GWP), excluding biogenic carbon, impact score referred to the functional unit (FU, here for each scenario it is defined as "1 MJ of Higher Heating Value (HHV) in the fuel produced") is shown for biogasoline and biodiesel produced in the three TCR/PSA/HDO thermal energy scenarios and for the demonstrator and commercial configurations, respectively (Figure 9). Both are compared to the respective conventional fuel, either gasoline or diesel, and to the RED II "fuel comparator value".

In conclusion, using natural gas as thermal energy source for the sewage sludge drying proves to be the worst choice if compared to the wood gasification and greenhouse scenarios, regardless of the TCR/PSA/HDO system configuration. The GHG emission savings for the natural gas scenarios do not achieve the 65% benchmark set by the RED II in any of the biofuels considered.
On the other hand, wood gasification and greenhouse scenarios represent way more promising solutions to meet the target. They indeed perform better than conventional fuels, both gasoline and diesel respectively, and largely achieve the 65% reduction of GHG emissions with respect to the RED II and the 80% with respect to the project specific KPI. It must be noted that in all scenarios analysed, the commercial TCR/PSA/HDO configuration allows for better results if compared to the demonstrator plant.
This shows the crucial role of implementing engineering strategies to recover energy and by-products whenever possible. Another important aspect, which applies to both configurations, is the phosphorus recovery from the pyrolysis ashes, leading to significant environmental credits thus lowering the overall GHG emissions of the system.

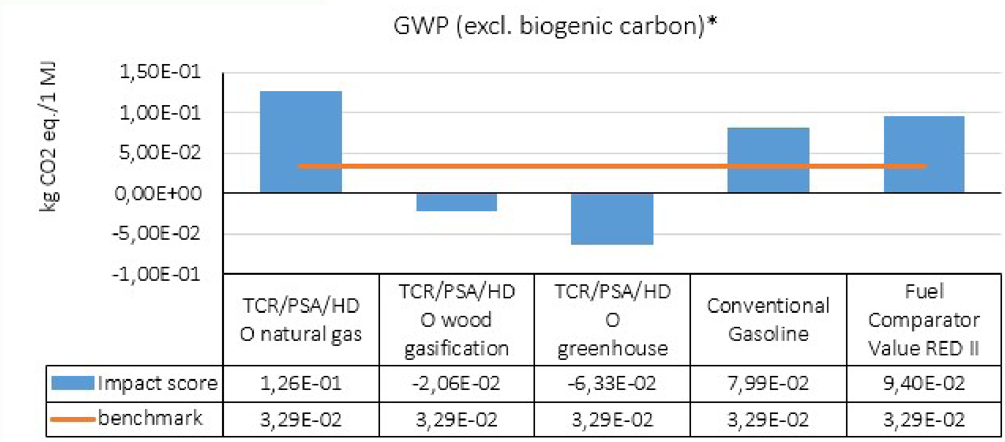


Figure 9: GWP (excluding biogenic carbon) results for the biogasoline produced at the *demonstrator 500 kg/h plant for the three thermal energy scenarios analysed and for conventional gasoline; RED II fuel comparator value is also reported, as well as the benchmark.

GHG emission savings (%)	NG	WG	GH
Biogasoline - Demonstrator 500 kg/h	-34%	122%	167%
Biodiesel - Demonstrator 500 kg/h	-35%	121%	167%
Biogasoline - Commercial 500 kg/h	-18%	130%	183%
Biodiesel - Commercial 500 kg/h	-20%	129%	183%

Table II: *NG=natural gas; WG=wood gasification; GH=greenhouse.
Credit: University of Bologna.

Social impact assessment

The LCA methodology has been applied also to evaluate and analyse the potential social impacts of TO-SYN-FUEL products on different stakeholder groups (Figure 10).

Results concerning the social impacts into the different stakeholder groups are not ready to be published in this document but will be obtained soon. Here, only results concerning potential consumers stakeholder group are analysed.

For the potential consumers stakeholder group, a public consultation was performed on summer 2020, through online surveys, available in three different languages: English, Spanish and Italian. 242 surveys were completed till the end of September.

The results of the survey revealed that the majority of the potential consumers (respondents) have declared to have a basic to advanced knowledge about biofuels (80%), and a basic to medium level knowledge about synthetic fuels (56%). The majority of the potential consumers (73%) also felt that synthetic fuels can substitute conventional transport fuels or may do so in the future. Another important result to highlight is that the potential consumers believe that wastes from biomass (e.g.: agricultural wastes, sewage sludge, cooking oil...) are the most sustainable raw materials to produce synthetic fuels.

Concerning the improvement potential of replacing conventional fuels with synthetic fuels (see Figure 11), the surveyed potential consumers attributed the greatest potential to the creation of (1) new circular economy models, followed by (2) climate change mitigation, the (3) creation of new jobs, and (4) technological innovation in the car and transport industry.

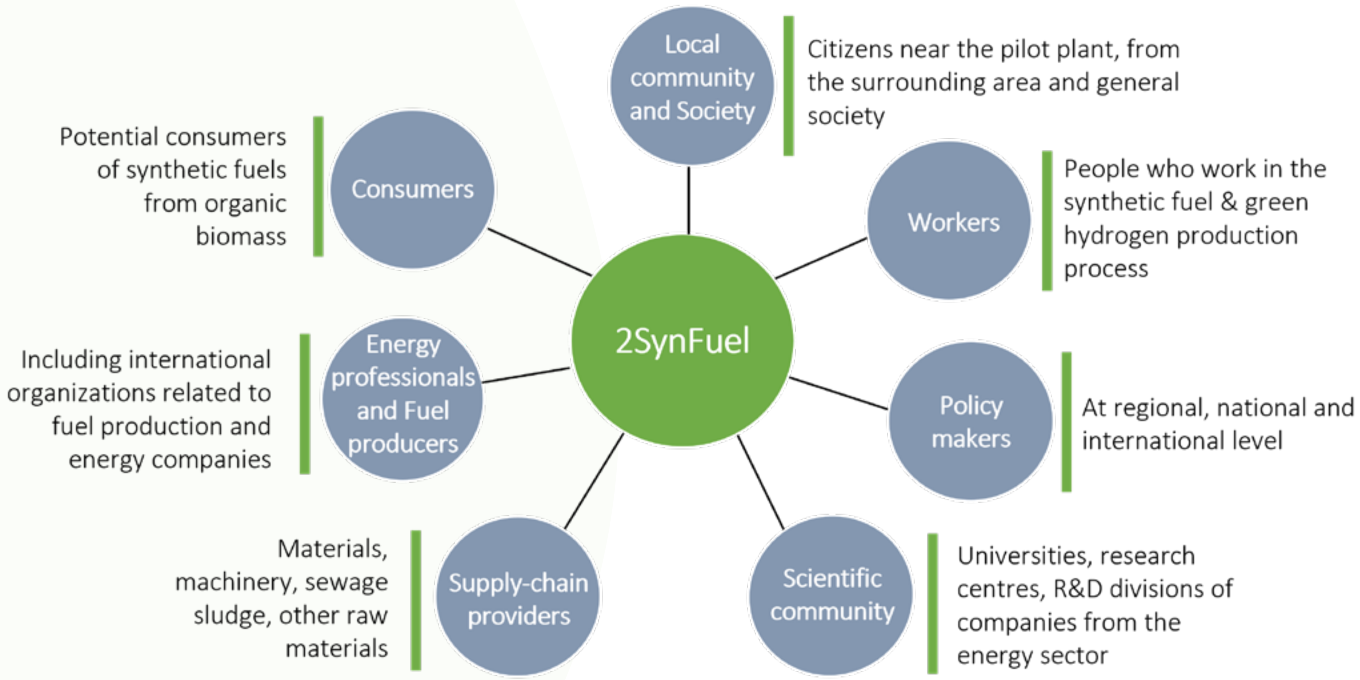


Figure 10. Stakeholders' groups defined and analysed in the Social LCA.
Credit: LEITAT.

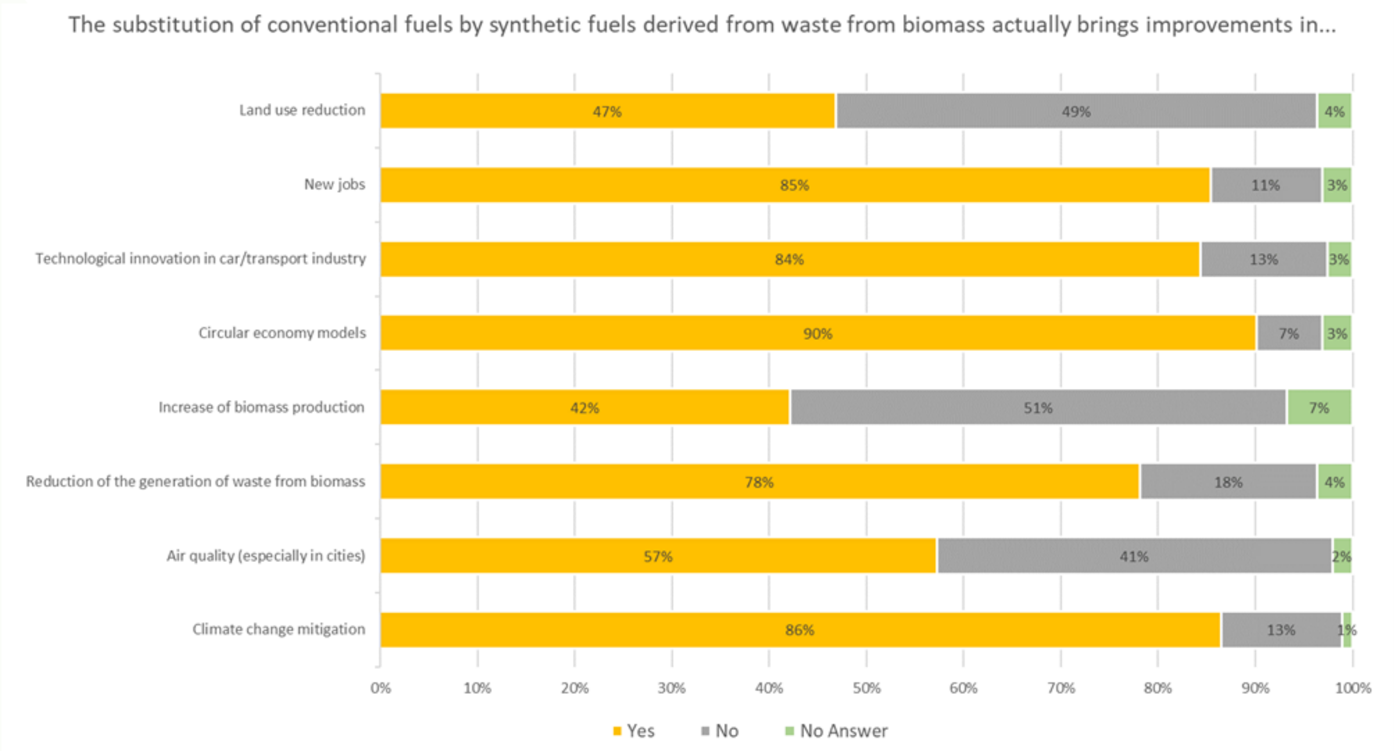


Figure 11. Improvements caused in eight different environmental and economic aspects because of the substitution of conventional fuels by synthetic fuels, according to the respondents' opinions (percentage).
Credit: LEITAT.

Regarding the main problems faced by synthetic fuels for market implementation, (1) the lack of policy adequacy to solve the current barriers to fully implement the use of sustainable synthetic fuels and (2) the lack of policy to promote the use of sustainable synthetic fuels were identified by respondents as the main barriers.
Respondents think that consumers distrust of quality or safety aspects relating to synthetic fuel consumption are not determinants for their market implementation.

Finally, a clear majority (93%) of potential consumers declared to be willing to use synthetic fuels derived from biomass waste in their vehicles, as well as a willingness to pay more (73%) for a more environmentally and socially sustainable fuel (see Figure 12).

In conclusion, it can be stated that, in general, synthetic fuels enjoy good acceptance by potential consumers but that clear and understandable communication strategies are needed to provide necessary information about synthetic and related fuels to potential consumers, including its environmental and social benefits and its impacts, to facilitate an informed decision making.

Finally, the exploration of potential consumers' perceptions of the sustainability of synthetic fuels showed that most of them (more than 90%) believe that fuels derived from biomass are more sustainable than conventional fuels (gasoline and diesel), as well as those fuels derived from biomass, and especially from biomass waste, are more environmentally and socially sustainable than conventional fuels (see Figure 12).

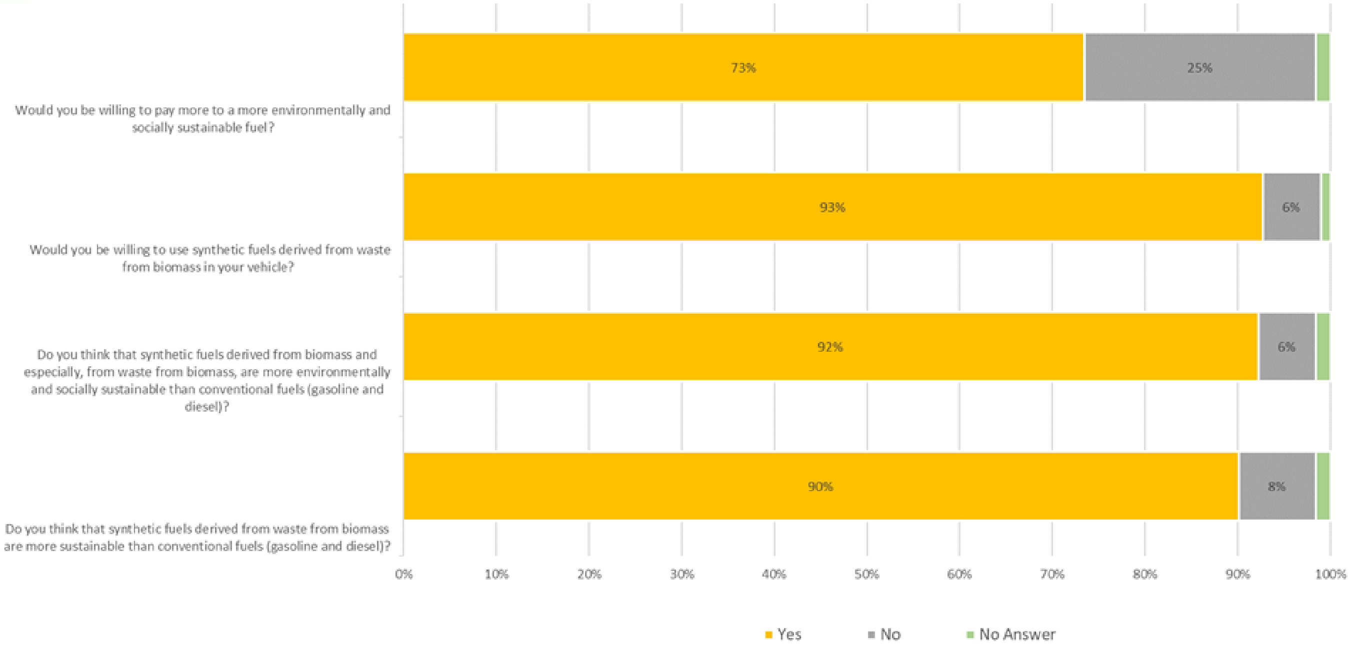


Figure 12. Potential consumers' perception of synthetic fuel sustainability, and willingness of the potential consumers to consume synthetic fuels (in percent).
Credit: LEITAT.

Evaluation of the risk posed to chemical compounds in the TCR/PSA/HDO plant

This assessment was carried out to evaluate the human health potential risks posed by the different chemicals used within the process of obtaining fuels for automotive (gasoline and diesel) from sewage sludge, which workers could be exposed during the manufacturing process.

A theoretical and quantitative risk assessment was performed to achieve the goal. This assessment involved the quantification of the Risk Characterization Ratio (RCR) by comparing the estimated exposure levels (associated to each component of the relevant products) to quantitative human hazard information [Derived no-effect levels (DNELs)].

The used methodology for the risk assessment, which includes hazard characterisation, exposure characterisation and estimation of Risk Characterisation Ratios (RCRs), was in line with the Guidance on Information Requirements and Chemical Safety Assessment, issued by ECHA within the framework of REACH Regulation. This methodology requires collecting toxicology information on the different components that conforms the different products.

The compilation of hazardous information (CLP classification) and human toxicological data of the selected substances was required for the hazard assessment, in order to characterise the most relevant endpoints for the risk assessment (including mainly Derived No-Effect Levels (DNELs)). Unfortunately, the available information at ECHA dissemination database was limited for most of the components that conforms the intermediate fuels and equivalent automotive fuels.

Furthermore, this approach does partially consider the interaction of each chemical compound in the whole product.

Exposure is a key element in risk assessment since it is a precondition for the potential toxicological effects to take place. This part of the assessment has been conducted by assessing the different stages of the process under consideration, starting with the collection of published information on the operational conditions (OC) and risk management measures (RMM) reported in different deliverables of TO-SYN-FUEL project and other contextual information to define the determinants of exposure. The following table list

the identified exposure scenarios where workers could be potentially exposed to chemicals:
Based on the collected information on operational conditions and risk management measures during the demonstration at industrial site in Hohenburg (Bavaria, Germany), estimated exposure values were obtained via a freely available software: ECETOC Targeted Risk Assessment.
Once the toxicological information was collected and the exposure values were estimated, the Risk Characterisation Ratios (RCRs) could be calculated for the relevant exposure scenarios where workers could be exposed to chemicals.
When the calculated RCR value is below to 1, the risk posed by a specific substance in the considered exposure scenario (in the considered route of exposure) is considered as safe for the human health and no further risk mitigation measures need to be implement for the carry out of the activity under assessment.
As general conclusion, it can be affirmed that ES01, ES02, ES04, ES05, ES06 and ES07 are exposure scenarios which are carried out under safe conditions for the human health of the workers, based on the available toxicity information of the chemical components in these products (as the calculated RCR were lower than 1).
This fact indicates that the expected exposure to the identified chemical compounds in the different fuels at the considered exposure scenarios does not exceed the exposure level to show negative effects to human health.

Therefore, they are within the chemical safety margin that Regulation (EC) nº 1907/2006 (REACH Regulation) establishes.

ES03 was initially not performed under safe conditions for workers, since the value for the RCR for "mixed alicyclic-aromatic 4" was higher than 1 (RCR = 1.64). However, this situation was reversed using globes, at least, APF 10.
The arrived conclusion on this theoretical assessment must be corroborated by the performance of experimental toxicity assays for each of the intermediate and final automotive fuels, as well as by the measurement of real exposure levels (no estimated).

Exposure Scenario	Description	Chemical compounds involved
ES01	Sampling of TCR bio-oil	TCR bio-oil
ES02	Mixing of diesel and DMDS for the initial set-up of the HDO unit	Diesel DMDS
ES03	Sampling of HDO bio-oil	HDO bio-oil
ES04	Replacement of the catalysts in the reactors R-4001A/B (configuration 1), after deactivation.	TK-455 MultiTrap™ SiC Diesel+DMDS HDO bio-oil
ES05	Replacement of the catalysts in the reactors R-4002A/B and R-4003A/B (configuration 2), after deactivation.	TK-431 SiC Diesel+DMDS HDO bio-oil
ES06	Sampling of raw diesel AV 266-1	Raw diesel AV 266-1
ES07	Sampling of raw gasoline AV 266-2	Raw gasoline AV 266-2

Table III: Identified exposure scenarios.
Credit: LEITAT.

5 Business cases

For the market entrance of the TCR technology four biogenic residues are identified as high potential feedstocks for the application of the TO-SYN-FUEL process (Figure 13). These are sewage sludge, digestate, manure as well as green and park waste. Especially sewage sludge offers a great potential, because more than a half of the total quantity in Europe is directly applied on fields or disposed on landfills. The TO-SYN-FUEL process offers an option to prevent risks from containing pollutants and to use its energy and nutrients content. For the use of manure and digestate as feedstock the TO-SYN-FUEL process should be installed in regions with a high density of livestock farming. Because of the limitation of the application on fields to avoid an over-fertilization, huge amounts of manure and digestate have to be exported from there, which can be used for the fuel production. Green and park waste offers the lowest potential of the four feedstocks referred to dry mass and it is the most expensive material. However, it is a high valuable feedstock especially for the further use of the produced biochar. This biochar has a high carbon or respectively low ash content and is therefore suitable for a wide range of applications.

A variety of technology approaches for the production of liquid biofuels was developed in recent years. These are on different levels of development. Already commercialized technologies apply mostly energy crops for the fuel production and not residues or waste. Two approaches based on fast pyrolysis apply a further upgrading step of the pyrolysis liquids to obtain fuels in accordance to the EN standards for gasoline and diesel, but these are on a basic research level and not proven. Therefore, the TO-SYN-FUEL approach is a very promising technology to produce liquid biofuels in accordance to the EN standards derived from biogenic residues on demonstration scale.

Figure 13: Pilot demonstration plant for the TO-SYN-FUEL project in Markt Hohenburg, district of Amberg-Sulzbach, Germany. Credit: Fraunhofer UMSICHT.

To assess the profitability of the TO-SYN-FUEL approach business scenarios for each of the four identified feedstocks were calculated and validated by a sensitivity analysis.

At a commercial scale of 3 t/h each of the four scenarios shows a potentially high profitability with respect to the assumed conditions.
However, the sensitivity analysis shows for the variation of the biochar price the highest impact to the results of the business case calculations. Therefore, the marketing of biochar should be a focus for each scenario. Low biochar prices can threaten the profitability.

A reason for that is the large quantity of produced biochar compared to the other products.

On the other hand, the price for the HDO oil has almost no impact to the profitability, even if it is the main product of the project. A reduction of the feedstock gate fee or respectively an increase of the feedstock costs can reduce the profitability, but it does not lead to an inefficiency. Only if the gate fee for manure will be reduced by more than 60% the business case becomes critical.

Finally, the variation of the CAPEX was examined as well. This is reasoned by the steady increase of equipment costs within the last years. An inefficiency was only observed for a CAPEX increase by 80% for the manure scenario. The CAPEX for this scenario is about 2-3 times higher compared to the other scenarios. Therefore, a price change for equipment has a higher impact there.

Credit: TO-SYN-FUEL Project.

6 Dissemination and public engagement

Since the beginning of the project in 2017, the consortium has ensured the participation of partners as speakers at leading events at both international and national level in order to address a broad range of audiences. This section is an overview of TO-SYN-FUEL contributions and participation at various events other than primary workshops, notably: EUBCE editions, other projects' workshops, symposiums, international conferences on energy and renewable fuels, etc. It should be noted that the social and travel restrictions imposed by Covid has meant public, scientific, and industrial engagement has been significantly hampered. However, wherever possible, digital substitution by virtual events has been implemented.

During the 29th edition of the European Biomass Conference and Exhibition (EUBCE), organised virtually by ETA, a first workshop was organized for enabling the TO-SYN-FUEL project to engage with the international community of bioenergy engineers and researchers, as well as international industry stakeholders.

Held virtually in the afternoon on Tuesday 27 April in the framework of the EUBCE 2021, the workshop "TO-SYN-FUEL project – Turning sewage sludge into fuels and hydrogen" made an overview of the project's progress and provided valuable insights on a number of topics: from feedstock supply chains, to technological aspects, risk management, and business cases.

On 27 April in the morning, Robert Daschner (Project Management Officer) took part in the Conference as a speaker in a Plenary Session dedicated to Alternative Fuels. On the same day in the afternoon, a workshop entitled "TO-SYN-FUEL project – Turning sewage sludge into fuels and hydrogen" was held in the Exposition area; this included presentations by multiple project's partners and involved a great number of participants.

The First Demonstration Day took place on the 22 September 2021, from 12:00 to 14:00 (CEST). The event comprised a first part with presentations to introduce project activities, and a second part with live streaming for the virtual plant visit (Figure 14) and a final discussion session. The whole meeting was held via MS Teams platform, where presenters and attendees were able to join virtually, and where the plant site visit was streamed live.

Figure 14: TCR-oil obtained from the TO-SYN-FUEL demonstrator plant.
Credit: TO-SYN-FUEL project.

A second workshop was held in the framework of the 30th edition of the EUBCE, in 2022, which was also conceived as the final conference of the project.

The TO-SYN-FUEL Final Conference titled "TO-SYN-FUEL plant to produce renewable fuels" took place virtually in the framework of the 30th EUBCE, on the 11 May 2022 from 12:15 to 13:45.
It was listed among the EUBCE Parallel Events with a dedicated webpage containing basic information, a description, and a detailed agenda of the event. Virtual participation was open to anyone registered at the EUBCE with a free Visitor pass.

The event has been widely promoted through project social media, and by exploiting the broad communication channels of the EUBCE.
The conference was dedicated to the TO-SYN-FUEL project entering its last phase. The current state of the project was illustrated, focusing on the demonstration that is currently running. The workshop included a live streaming from the project's demonstrator plant in Hohenburg, conceived as a virtual tour.

The plant tour experience was properly framed by a series of presentation during the workshop, concerning the following aspects: characterisation of processed feedstock (sewage sludge) and main products from the process (H_2-rich syngas, biochar and bio-oil), core component of the integrated technology, first results of the study on stakeholders' perceptions towards the project technologies, and promotional initiatives proposed to engage industry.

The consortium is working hard on communication at both national and international levels. One of the most significant is a promotional Car Tour planned between 15-28th September 2022 (Figure 15).

Figure 15: Promotional Car Tour planned this September 2022: a car, fuelled with TO-SYN-FUEL diesel.
Credit: WRG E urope.

A car, fuelled with TO-SYN-FUEL diesel, will stop at locations around Europe, including filming at an autodrom with rally legend Walter Rohl, interviews at Bayern Oil and Fraunhofer HQ, and a premium showcase presentation at this year's European Sustainable Energy Week 2022.

EUSEW is taking place on 26-30 September to promote the technology and the importance of biofuels in the clean energy solutions mix for greener transport for now and for in the medium-to-long term.

7 Conclusions

By demonstrating all the essential process steps in an industrial operational environment, the project advances the technology's technical readiness to level 7 while achieving the main aim of the project, which is the long-term operation of a pre-commercial demonstrator. This is the final step of development before the technology reaches full commercial scale.

The testing campaigns with TCR have shown very satisfying performance, with the biocrude oil quality being in line with expectations. Also, the business plan and the socio-environmental sustainability analysis for the process provide very positive outcomes.

The integrated approach has been designed to be economical at a small scale. The intention is for the demonstration site to be located near to a variety of organic waste producers and, potentially, petrochemical industries.
This means that the concentration of potential end users of the integrated approach will be high.

By locating the plant close to these feedstocks TO-SYN-FUEL will be able to engage with these waste generators and demonstrate to them the value of the approach thus facilitating their involvement in the next phase as feedstock providers to the commercial flagship plant.

Credit: TO-SYN-FUEL Project.

8 References

A selection of reports from TO-SYN-FUEL as reference and for further reading

D2.1, Feedstock composition and system mass/energy balance.

D2.7, Fully assembled integrated plant.

D2.8, Safety tested and fully operational TCR/PSA/HDO plant.

D2.9, A Fully Operational TCR/HDO/PSA Plant.

D3.1, Mass and energy balance for plant at steady state.

D3.6, Plant decommissioned.

D3.7, Demonstration of an integrated TCR/PSA/HDO plant at Hohenburg using locally sourced feedstocks.

D4.1, Data describing consistency of feedstock composition.

D4.3, Characterisation of synthetic diesel and synthetic gasoline fractions.

D4.4, Validation of synthetic fuels as fuel analogue based on 50000 mile engines test.

D4.5, Performance results of residual syngas for CHP generation.

D4.6, Performance results of char for generation of energy through gasification.

D4.7, Pot trials complete and report analyzing the ability for nutrient uptake from char and ash.

D4.8, Full ash characterization in terms of heavy metals.

D4.9, Data sets from upgrading of chars to improve plant effluent water quality.

D4.10, A full range of analytical data on feedstocks, products and wastes produced by the demonstration, combined with successful testing for use of the fuels produced in road applications.

D5.1, Description of consumer perceptions towards synthetic fuel products.

D5.2, Map of positive and negative perceptions of local/regional stakeholders towards the integrated TCR/PSA/HDO technology.
D5.3, Evaluation of occupational health risks associated to the integrated TCR/PSA/HDO technology.
D5.4, Social sustainability report describing the social impact of the 5 TCR/PSA/HDO expected on the local and regional community and project stakeholders.
D6.1, State of the art LCA model for TCR application selected.
D6.2, Definition of scope of sustainability metrics.
D6.4, Map of scenarios for alternative use of feedstocks.
D6.6, GHG savings quantified.
D6.7, LCA of commercial scale TCR/PSA/HDO unit.
D6.9, Comprehensive environmental sustainability report.
D7.3, Business potential analysis report.
D8.4, Catalogue of regulatory issues.
D8.5, Regulatory impacts and risks scenarios in business development.
D9.2, Branding materials.
D9.3, Website and social media feeds online.
D9.4, Final press review.
D9.5, Hosted TO-SYN-FUEL demonstration days.
D9.6, Conference day proceedings.
D9.7, List of publications in trade magazines.
D9.9, Final public oriented report and public outreach programme complete.

About the project

The consortium with 11 partner organisations has brought together some of the leading researchers, industrial technology providers and renewable energy experts from across Europe, in a collaborative, committed and dedicated research effort to deliver the overarching ambition. Partners include: Engie Services Netherlands NV, HyGear Technology and Services BV (The Netherlands), Fraunhofer UMSICHT, Verfahrenstechnik Schwedt GmbH, Martech GmbH (Germany), Alma Mater Studiorum – University of Bologna, Eni SpA, ETA–Florence Renewable Energies (Italy), University of Birmingham, WRG Europe Ltd (UK) and LEITAT (Spain). The project has a total duration of 65 months from May 2017 to September 2022 and is funded by the European Union under the Horizon 2020 programme.

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Disclaimer

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