Assessment of successes and lessons learned for biofuels deployment

Report Work package 3 | Case studies technologies

IEA Bioenergy TCP

IEA Bioenergy: Task 39 + 40 + 45

June 2023

Assessment of successes and lessons learned for biofuels deployment

Report Work Package 3 | Case studies technologies

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Executive summary

Approach

This project "Lessons Learned Biofuels" comprise five Work Packages with respective reports. In the work package presented in this report (WP3), case studies are accessed to illustrate example of successful progress in developing and scaling up conventional/existing and advanced/emerging biofuels production technologies. In addition, lessons learned in shortcomings or problems or other issues in the commercial development are also given in the case studies.

Specific case studies have been investigated, being the countries included Germany, Sweden and Canada. Example of the technologies have chosen based the expertise of the members and the maturity of the technology, being that to be considered a success story, it was chosen the criteria of minimum Technology Readiness Level (TRL) 7.

Prior the case studies the Work Package 2 formed a meta-analysis of existing studies which yielded the following conclusions, which are all of importance in understanding the whole picture which also includes the case technologies in this report.

- Conventional biofuels such as ethanol (both sugarcane and corn) and biodiesel are produced in substantial quantities and on market in several countries. These are as of now the most important biofuels to replace fossil fuels in the world.
- Yields, costs and environmental indicators have improved with time.
- Mandates and proper public policies were important to support implementation and technological improvements.
- Economic crises (Covid, war) affected biofuel mandates and use in several countries. This led to advances in biofuel production and use of past years will have to be recovered.
- Published indicators for cellulosic or "advanced" ethanol are seldom available. There is evidence that technological bottlenecks are being overcome.
- Although feedstock issues apply in some countries, lessons learned with these biofuels turned them into relevant benchmarks and set standards for novel biofuels with low TRL
- Biomass-to-liquid, bio-CNG, HVO, and straw-derived advanced ethanol show suitable indicators of environmental impact, SDG, and feedstock diversity to be replicated in different regions.
- Technological and cost limitations must be overcome.

Key messages

Thus, the following case studies technologies conclusions are:

- Case studies with biofuel technologies for selected countries Germany, Sweden and the USA
- Analysis has identified technology successes and the best policy framework conditions and measures for stimulating increased future markets

- Most critical factors for identifying risks in financing new production plants:
    - Secured biomass supply/local feedstock availability with feedstock price
    - Stability of the regulatory framework, longer perspective, binding mandates;
    - CAPEX dimension & financing
    - Financing of first technology type plant requires higher guaranteed biofuels price than following plants.
- Political decisions ultimately and irrevocably determine success of biofuel production projects.
- As technology matures after first technology type large plant biofuels regulation can gradually be shifted from specific to general. Biofuels quotas clearly cannot support new technology and large 1st of its kind plants, without additional security on value of renewables.
- Key: “The biofuel must comply with existing infrastructure”
  Implying: Very complicated/costly with new infrastructure (example AFID in EU)

In the supply chain work package of this project the following key messages are of importance as well in completing the picture of success and lessons.

- Feedstock quality considerations, emanating from impurities and contaminants are important, yet mitigation methods such as feedstock blending can help deploy advanced feedstock processing systems effectively.
- Biomass harvesting and processing can be accomplished with a wide array of equipment and collection systems, modified foragers and/or in-field chopping can provide an effective alternative across different feedstock systems.
- Torrefied biomass does behave superior to untreated densified biomass, saves energy and costs along the supply chain, and will open up new markets for biomass to substitute hydrocarbons and coal.
- Facilitating the shift and scale up of (advanced) biofuels from road transport to aviation and maritime sectors will remain a challenge, but technical innovations and economies of scale can result in substantial cost reductions.

For respective conclusion of case studies technologies it is referred to case studies technologies chapter but the overall key messages which forms a combined result and takeaway are this.

> Different projects investigating experiences and possible drivers and barriers for biofuels and trying to provide guidelines for decision makers. Following some of them and including the results of this lessons learned study
>
> Key message of almost all studies:
>
> 1. Continuously work on harmonized clear long-term policies that allow improvement of established biofuel options as ground base for decarbonization in transport.
>
> 2. This is urgently needed for a sustainable carbon neutral world R&D&D of innovations of advanced biofuels incl. hybrids with other renewables that are more complex and thus (usually) more cost demanding (e.g. with regard to GHG mitigation).

1. Introduction

1.1. Background

There are major challenges associated with achieving a CO2 (GHG emissions) neutral society by 2050 and fulfilling sustainable development goals (SDGs) and the IEA's Sustainable Development Scenario (SDS). Among societal sectors, transport is proving to be an extremely difficult sector to decarbonize – from fossil carbon to renewable carbon based fuels, with IEA analysis showing the rate of progress well below what is needed to sufficiently contribute to the SDGs.

Transport biofuel production is expected to continue growing, however, only at annual rates below 5% according to IEA in the near future, whereas sustained levels of 10% output growth per year are needed until 2030 to get on track with SDS. The bottom line is that despite billions of dollars of investments, ramped up production of low carbon advanced biofuels remains well below the levels needed to achieve the SDS.

Stronger policy support and a greater rate of innovation are required to reduce the costs of development and scale up of sustainable advanced biofuel production, particularly for sectors like heavy duty transport, aviation and marine, which are especially hard to decarbonize. This intertask project seeks to analyze international progress and experiences to identify which approaches are proving to be most effective so they can be expeditiously and more broadly deployed to get transport decarbonization back on track with SDS goals.

1.2. Purpose and objectives

This project will evaluate the technical, economic, societal and political reasons underlying the past and ongoing booms and busts cycles of biofuel technologies development, demonstration, deployment and replication in order to identify technology successes and the best policy framework conditions and measures for stimulating increased future markets for production and consumption of sustainable transport biofuels.

The project essentially starts from two basic research questions with the aim to find the answers to:

- "What are key factors for the success of sustainable advanced biofuel projects?" and
- "What is required to re-stimulate vigorous biofuels development and commercialization?

1.3. Activities and results

The project "Lessons Learned Biofuels 1" was divided into six Work Packages (WP). In the work package presented in this report (WP3), case studies are accessed to illustrate example of successful progress in developing and scaling up conventional/existing and advanced/emerging biofuels production technologies. In addition, lessons learned in shortcomings or problems or other issues in the commercial development are also given in the case studies.

The structure for the project is shown in the Figure 1, in which the division of the work packages and the lead of which one is presented, distributed in the IEA Bioenergy Tasks (T39, T40 and T45). It is foreseen a continuation of the project in a Phase 2, described in the figure as "Lessons Learned Biofuels 2".

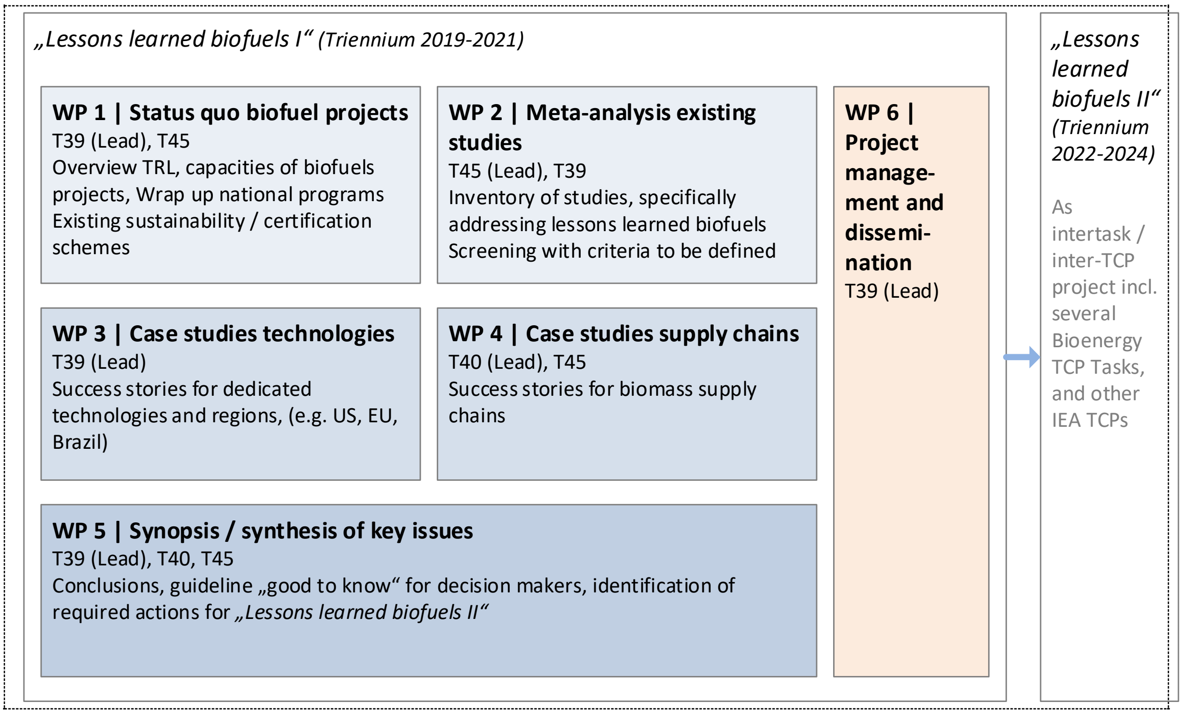

Figure 1. Project Work Package structure.

The different Work packages are briefly explained and for further reading of these it is referred to the other reports which were published in this project.

Work package 1 | Status quo biofuel projects

Overview on conventional biofuel capacities, including a brief summary of the development and status of advanced fuel projects worldwide. It describes issues related to governance of biofuel development, e.g., mapping and inventory of existing policy instruments (e.g. targets, quotas, sustainability requirements, top runners, etc.) and their impact/success.

Work package 2 | Meta-analysis on existing studies

There are several studies that are investigating “successes and lessons learned for biofuels deployment” on a direct or indirect level for different fuel options. This WP performs meta-analysis on existing studies. After screening of relevant studies, criteria need to be identified for the analysis that allow comparing the different studies and to compile the results of the analysis in a comprehensive summary of conclusions.

Work package 3 | Case studies technologies

Specific case studies for countries including Germany, Sweden and Canada. For each country there will be cases, i.e. biofuel projects or plants. In addition each country policy will be analysed in terms of successes or lessons in terms of the projects and plants.

Based on the meta-analysis in WP 2, a template with some criteria will be developed in order to allow comparing these prominent examples. Such a template could include, e.g.:

- Indication | e.g., name and or ™, fuel option, location
- Technology characteristics | e.g., feedstocks and products (incl. their quality), process design, licence provider, plant manufacturer, operator, chronicle of technical success, plant sizes/capacities as well as continuous operation related to different TRL/FRLs along the innovation chain, challenges to be met/technology learning
- Value chain | e.g., included stakeholders, feedstocks origin (like local/abroad), product market (like local/abroad), volume logistics, decoupling of processes (e.g. feedstocks pretreatment or final product treatment etc.)
- Sustainability related to economics | e.g., planned CAPEX, (OPEX), realized CAPEX (OPEX), business model (e.g. cofinancing via governmental funding programs or venture capital), subsidies for feedstocks and products, economic learning
- Sustainability related to climate/environment | e.g., relevant certification schemes, local impact (e.g., related to local impurities, waste water treatment)
- Wrap-up of success | e.g., technical success, proper frame conditions

Work package 4 | Case studies supply chains

The lessons learnt in supply chains, sustainability certification, standards and developments of markets of biodiesel, methanol, wood chips and wood pellets are highly relevant for new biomass markets including bio-based chemicals and advanced biofuels. Cost-effective, reliable and sustainable feedstock supply chains are crucial to a successful development of advanced biofuels. Advanced biofuels will develop in an increasingly internationalized market with respect to tradeable feedstocks as well as international end-use markets such as shipping and aviation.

Work package 5 | Synopsis / synthesis of key issues

Providing a synopsis of this study, in the light of above mentioned research questions WP5 is dedicated to drawing conclusions about "Successes and lessons learned on biofuels deployment" and developing a kind of "guideline/good to know" brief for decision and policy makers. Additional outlook-oriented parts of this work package include identifying objectives for further – and in terms of dedicated questions – more detailed aspects of "Assessing lessons learned for renewable fuels".

1.4. Case studies technologies

In this work package specific case studies were investigated, being the countries included Germany, Sweden and Canada. Example of the technologies were chosen based the expertise of the members and the maturity of the technology, being that to be considered a success story, it was chosen the criteria of minimum Technology Readiness Level (TRL) 7. The different groups of levels of technology used in this report are the following with:

- TRL 1-2 (Basic research),
- TRL 2-5 (Applied research) and
- TRL 5-8 (Technical development) and
- TRL 9 (System proven in operational environment).

For more broad description of levels please see below Figure which defines the states from TRL 1-11, whereas levels above 8 have not been the scope of the study as they are true commercial systems widely adopted.

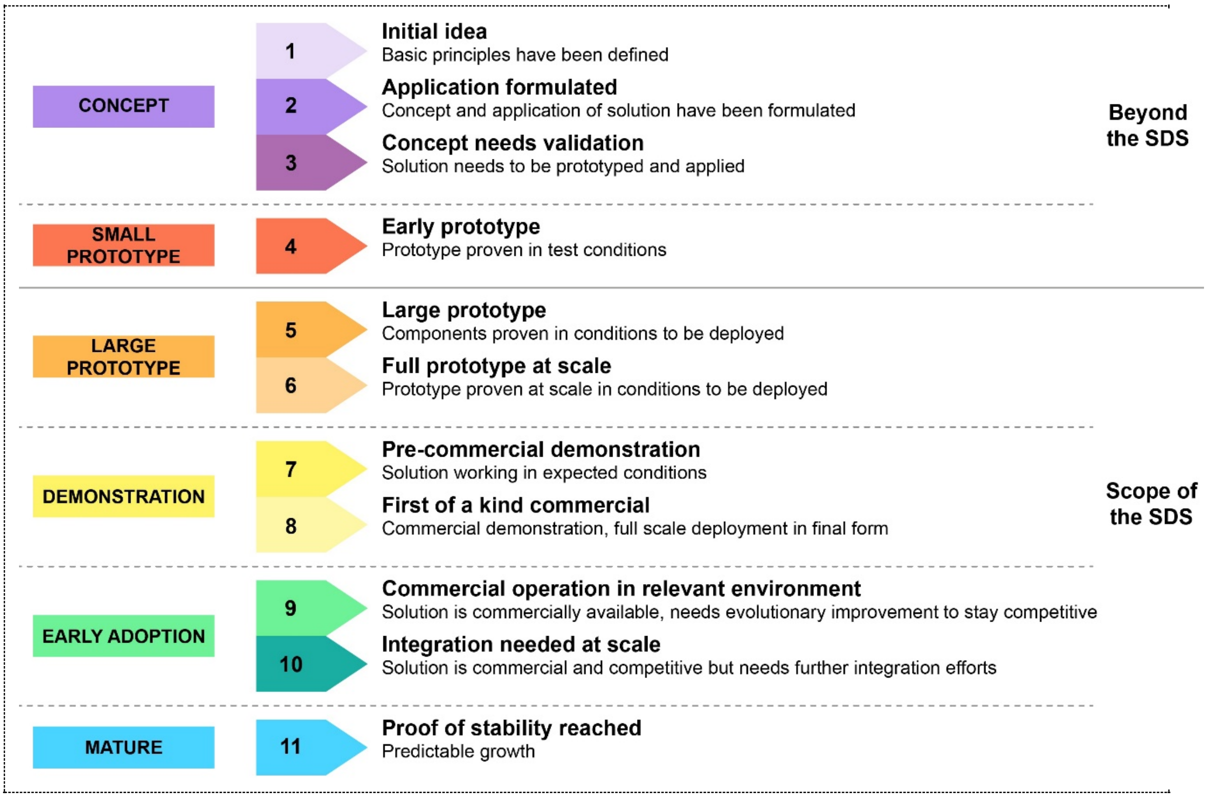

Figure 2. Technology Readiness Level (TRL) according to IEA.

The aim was to have analysed for each country a minimum of two cases, i.e. biofuel projects or plants. In addition each country policy will be analysed in terms of successes or lessons in terms of the projects and plants.

2. Methodological approach

2.1. Characteristics

For the elaboration of each case study, it was elaborated a template for fulfilment, in which characteristics of the selected technology/project were included, as:

- Indication | e.g., name and or ™, fuel option, location
- Technology characteristics | e.g., feedstocks and products (incl. their quality), process design, licence provider, plant manufacturer, operator, chronicle of technical success, plant sizes/capacities as well as continuous operation related to different TRL/FRLs along the innovation chain, challenges to be met/technology learning
- Value chain | e.g., included stakeholders, feedstocks origin (like local/abroad), product market (like local/abroad), volume logistics, decoupling of processes (e.g. feedstocks pretreatment or final product treatment etc.)
- Sustainability related to economics | e.g., planned CAPEX, (OPEX), realized CAPEX (OPEX), business model (e.g. co-financing via governmental funding programs or venture capital), subsidies for feedstocks and products, economic learning
- Sustainability related to climate/environment | e.g., relevant certification schemes, local impact (e.g., related to local impurities, waste water treatment)
- Wrap-up of success | e.g., technical success, proper frame conditions

With the points described above, it is possible to access the timeline of the development of the technologies and have insights on the success factors for the scale-up. The projects were selected according to the recommendation of the experts of the Tasks 39, 40 and 45.

2.2. Selected technologies

In the Table 1 is described which case studies were selected for the utilization as lessons learned for technology development of biofuels. These are further detailed in Chapter 3.

Table 1. Case studies covered in the Work Package.

Case study and company	Technology	Country
Clariant – Sunliquid®	Cellulosic ethanol	Germany
KIT – Bioliq® platform	Gasification and fuel synthesis: Biomass-to-Liquids	Germany
Choren - BTL	Gasification and FT-Synthesis: Biomass-to-Liquids	Germany
Chemrec - BLGMF	Black liquor gasification to fuels methanol/DME	Sweden
GoBiGas	Biomass gasification to methane	Sweden
SunPine	Tall oil esterification and hydrogenation to HVO	Sweden
Enerkem	Waste gasification to alcohol	Canada

Each template was firstly filled with information found in the literature, which was collected from the members of the work package. After completion of first draft, if possible, experts engaged with the technology were contacted to comment the case study. It is indicated in which case study if information from external contact was gathered.

In addition, one the authors of this report, Tomas Ekbom, has been working for 18 years as industrial developer and consultant and has deep knowledge and expertise in the technologies detailed (except for Clariant). In his work, large set of documents have been examined over the years which forms some of the information and comments in this report.

Therefore, some of the comments are or personal matter and can be seen as an expert opinion. As always, there may be other opinions and information that contradict certain statements. Still, this compiled information is of high-level and serves the scope and objective of this project and report.

With three cases for Germany and three for Sweden this is more than the aim. However, for Canada one was completed and none for Brazil. In the case of Brazil the bagasse fermentation to ethanol (Cellulosic ethanol) would have been of interest but with Clariant this is covered for most parts. This goes also for USA and Poet with cellulosic ethanol. Another area is pyrolysis to HVO like for Kior, USA. However, this is in part covered by Bioliq and Choren.

There are other technologies which are of interest but the difficulty and scope of the project made it necessary to limit to the seven cases analysed in this report. Last, with the Gobigas plant also gas product is covered and hence essentially all advanced biofuels are featured in this report from ethanol, methanol to DME, Bio-CNG and Fischer-Tropsch Diesel and lastly HVO with also biokerosene and biochemicals.

3. Case studies technologies

3.1 Clariant – Sunliquid® Enzymatic hydrolysis to ethanol

3.2 KIT – Bioliq® Biomass gasification with synthesis

3.3 Choren – Gasification and Fischer-Tropsch synthesis

3.4 Chemrec – Black liquor gasification with motor fuels

3.5 GoBiGas - Biomass gasification with methanation

3.6 SunPine – Esterification and distillation of tall oil

3.7 Enerkem – Waste gasification for alcohol production

Clariant Sunliquid® - Enzymatic hydrolysis to ethanol

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

Clariant AG

CURRENT STATUS (2023)

Location:	Germany, Bavaria, Straubing Germany, Bavaria, Planegg Romania, Dolj county, Podari
Technology:	Sunliquid® - Chemical-free pre-treatment, enzyme production, enzymatic hydrolysis, fermentation and product separation
Principle feedstocks:	Wheat straw, corn stover, miscanthus, sugarcane bagasse (domestic feedstock)
Products/markets:	Cellulosic ethanol and surplus electricity Demonstration plant with output of 1,000 t/year ethanol Designed to 50,000 – 150,000 t/year ethanol. Facility in Podari (Romania) with 50,000 t/year output, construction completed in autumn 2021
Technology Readiness Level (TRL):	TRL 8 – system complete and qualified

SHORT DESCRIPTION

The Sunliquid® technology processes lignocellulosic feedstock and converts it in five distinct steps. The first phase consists of a chemical-free pre-treatment (steam explosion), which aims at making the polymers of the utilized feedstock accessible. Part of the pre-treated biomass is used for an in-house production of enzymes, which are used to enzymatically hydrolyze (saccharification) the remaining cellulosic part of the pre-treated biomass. The hydrolysis consists in transforming the cellulose and hemicellulose fractions present in the biomass in sugar monomers that can be fermented. In the Sunliquid® process, the fermentation of sugar with 5 and 6 carbons occurs in parallel (alternatively the fermentation of 5 and 6 carbons sugars can occur separately).

The fermentation converts these sugars into bioethanol, which can then be purified by proprietary separation process from Clariant[5]. The process has two main by-products, one of them the lignin, which is burned to supply the facility with energy and steam (utilization of its energetic value). The other by-product is the vinasse, which is an organic liquid mixture that is separated from alcohol in the distillation columns, and due to its composition (rich in N, P and K) can be used as fertilizer.

Figure 1: The Sunliquid technology displayed at Podari plant (© Clariant)[4]

The Sunliquid® technologies first development steps were done through developing microorganisms and enzymes that could be utilized to process the lignocellulosic pre-treated feedstock (TRL 1-2), which enabled Clariant to open a pilot plant to operate and upgrade its unit operations (TRL 2-5). After the successful operation of its pilot plant, the scale-up to a demonstration plant was done in 2012 and operated in relevant conditions for 6 years (TRL 6-7) as a basis for the scale-up into commercial scales[4].

Due to its high innovation potential and its technological feasibility and competitiveness with fossil-based alternatives, the project receives a funding of EUR 48 million from the European Union through the projects SUNLIQUID[10] and LIGNOFLAG[11]. The objectives of the projects were the selection of a site for the implementation of a full commercial facility (first-of-a-kind), establish a highly efficient feedstock supply and logistics system as well as contracting local farmers and logistic providers for straw supply, transportation and storage.[6]

Further objectives are establishing an energy self-sufficient, highly sustainable production process for cellulosic ethanol by using co-products for renewable energy production and soil fertilization as well as developing a commercialisation strategy that includes distribution and marketing measures for cellulosic ethanol and the Sunliquid® technology.[7] With that, Podari in Romania was selected to receive the construction of the facility[4]. The facility started the construction in September 2018 and is expected to be finalized by the end of 2021[10].

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period	<2006	2006-2012	2012 – 2018	2018-2021
Driving frame conditions (which policy frame and/or society pushed the R&D focus)	Utilization of lignocellulosic feedstocks	Development of integrate biorefinery to process lignocellulosic materials[8,9]	Valorisation of agriculture residues	
R&D focus related to the technology itself	Research in microorganisms and enzymes adapted to the process[4]	Optimization of technology process in pilot plant[4]	Operation of demonstration plant in relevant environment to integrate process[4]	
R&D focus related to accompanying topic		Process optimization Expansion of usable biomass resources (Lignocellulosic biomass) Development and evaluation of integrated biorefinery concepts[9]	Clariant reports over 95% GHG emissions and negative emissions if considered carbon capture[4]	
Involved actors (from academia and industry) and their role		Clariant[9]	Clariant, EC FP7, BBI JU, farmers, local service providers	Clariant, License buyers in Slovakia, Poland, China and Bulgaria.

Public funding? If yes, mentioned the program		Yes	EC FP7, BBI JU Over EUR 40 million funding from the European Union[4] Grant 322386 named SUNLIQUID[6] Grant 709606 named LIGNOFLAG[7]	
Economic factors			Total investment: Over EUR 100,000,000[4]	
Driving factors for success		Funding to projects focusing the technology development with industry/research Expertise from institutions in the process development		Policies focused in GHG reductions targets (e.g. RED II, perspective RED III)
Lessons for other projects				Clariant as technology lincence provider

Information on SDGs and esp. factors with regard to economics and environment

The project contributes with the SDGs, seen that the conversion of residual biomass, for example the usage of straw in the first-of-a-kind project in Romania, does not compete with food/ land use. It also reduces GHG to about 95% compared to fossil fuel emissions[4].

Within the construction of its first-of-a-kind commercial Sunliquid plant in Romania about 800 workers have been hired for the construction of the facility. As of today, the site currently employs around 75 people. They benefit from intense training in Germany at our Straubing site. The collaboration Clariant has with the University of Craiova also helped develop the required skills[10]. In addition, contracts with more than 300 local farmers have been signed to ensure the supply of the necessary feedstock.

Wheat straw usage as feedstock enables the technology to be replicated on international level. Another important aspect is the self-production of enzymes, which enables the construction in remote areas, which do not depend on enzyme imports for the continuous operation[3].

The Sunliquid® technology can be described either as a technology success or a commercial success. The project went through all steps of developing a technology, scaling-up the technology maturity and testing its process in continuous operation for sufficient time to scale-up into a first-of-a-kind project, which is expected to be finalized in 2022. So far, five commercial licenses in Europe and China have been sold.

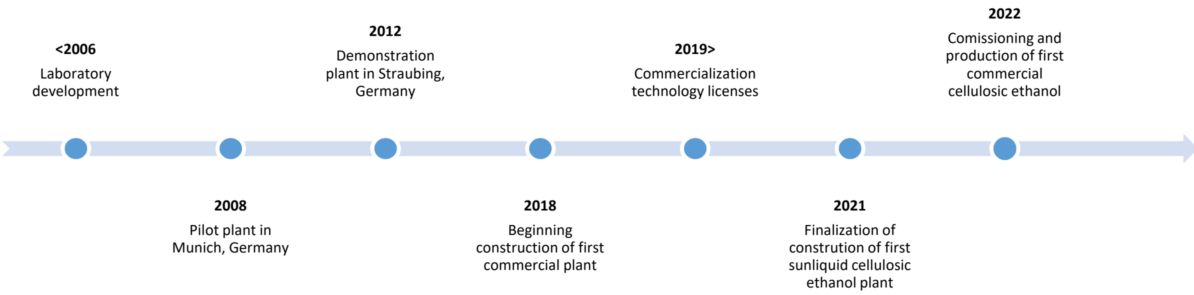

Figure 2: Timeline of the project

Figure 3: The Sunliquid cellulosic demonstration ethanol plant in Germany (© Clariant)[10]

Figure 4: The first commercial Sunliquid cellulosic ethanol plant in Romania (© Clariant)[10]

Info provided by: Dr. Ralf Hortsch, Head of Strategy & Marketing, BL Biofuels & Derivatives
Caroline Schmid, Global Marketing Manager, BL Biofuels & Derivatives
Gabriel de Paiva, DBFZ

More information:

1 http://artfuelsforum.eu/wp-content/uploads/2020/02/Success-Stories.pdf

2 https://demoplants.bioenergy2020.eu

3 https://www.biofuelsdigest.com/bdigest/2018/09/16/looking-deeper-into-clariant-cellulosic-technology-part-1-of-2-a-visit-to-straubing-germany-and-an-integrated-pilot-plant

4 https://www.clariant.com/pt/Company/Contacts-and-Locations/Key-Sites/Romania

5 https://www.clariant.com/en/Business-Units/New-Businesses/Biotech-and-Biobased-Chemicals/Sunliquid

6 https://www.sunliquid-project-fp7.eu

7 https://www.lignoflag-project.eu

8 https://www.tib.eu/de/suchen/id/TIBKAT:774535687

9 https://www.tib.eu/de/suchen/id/TIBKAT:781304644

10 https://bioenergyinternational.com/biofuels-oils/clariants-sunliquid-ethanol-plant-in-romania-on-track-for-2021-completion

Annex: Further guidance *(delete this section in final factsheet)*

A "success story" is defined as a project that is implemented, is operating at scale, contributes to the UN Sustainable Development Goals (SDGs), has wide replicability and large scale-up potential.

Replicability and/or scale-up potential

R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	l
S	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	L

Sustainability: Relation to SDGs

SDG

	SDG	
☐	1 No poverty	End poverty in all its forms everywhere
☒	2 Zero hunger	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**
☐	3 Good health and well-being	Ensure healthy lives and promote well-being for all at all ages
☐	4 Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
☐	5 Gender equality	Achieve gender equality and empower all women and girls
☐	6 Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all
☒	7 Affordable and clean energy	**Ensure access to affordable, reliable, sustainable and modern energy for all**
☐	8 Decent work and economic growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
☒	9 Industry, innovation and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
☐	10 Reduced inequalities	Reduce inequality within and among countries
☐	11 Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient and sustainable
☒	12 Responsible consumption and production	**Ensure sustainable consumption and production patterns**
☒	13 Climate action	**Take urgent action to combat climate change and its impacts**
☐	14 Life below water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
☒	15 Life on land	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**
☐	16 Peace, justice and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
☐	17 Partnerships for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development

***Note: Bold text means** SDG is directly related to biomass*

KIT Bioliq® - Biomass gasification with synthesis

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

Karlsruhe Institut für Technologie

CURRENT STATUS (2023)

Location:	Germany, Baden-Wuerttemberg, Eggenstein-Leopoldshafen, Karlsruhe Institute of Technology Campus North
Technology:	2-5 MW_{th} pilot plant with fast pyrolysis of lignocellulosic biomass, high-pressure entrained flow gasification of biosyncrude, high-temperature high-pressure gas cleaning/conditioning as well as methanol/dimethyl-ether and gasoline synthesis
Principle feedstocks:	Lignocellulosic feedstock (in the pilot plant straw and Miscanthus was used, the technology is applicable to diverse lignocellulosic feedstock)
Products/markets:	Transportation fuel: gasoline (max. 100 kg/h). The syngas can be used to produce other transportation fuels (e.g. diesel, kerosene) and also platform chemicals[2]. In container type plants, methanol, DME and oxymethylene ether and Fischer-Tropsch hydrocarbons are produced in kg/h scale.
Technology Readiness Level (TRL):	TRL 6-7 – system prototype demonstration in operational environment[2] Fast pyrolysis with High pressure entrained flow gasification and gas cleaning/conditioning (TRL 6) Methanol/DME synthesis and Gasoline synthesis (TRL 8)

SHORT DESCRIPTION

The Biomass-to-Liquids (BtL) Bioliq® process is divided in two steps, one decentralized and the other one centralized. In the first one, residual, lignocellulosic biomass is pre-treated by fast pyrolysis to produce an energy dense intermediate, biosyncrudes (heating value similar to coal[1]), which is collected and processed in the centralized process by high pressure entrained flow gasification to produce syngas typically at the proportion 1:1 H_2:CO. The synthesis gas is cleaned and conditioned prior to the one step methanol/dimethyl ether (DME) synthesis, from which gasoline is produced in the next step. By produced electricity and heat are utilized to cover most of the energy demand of the entire process[1].

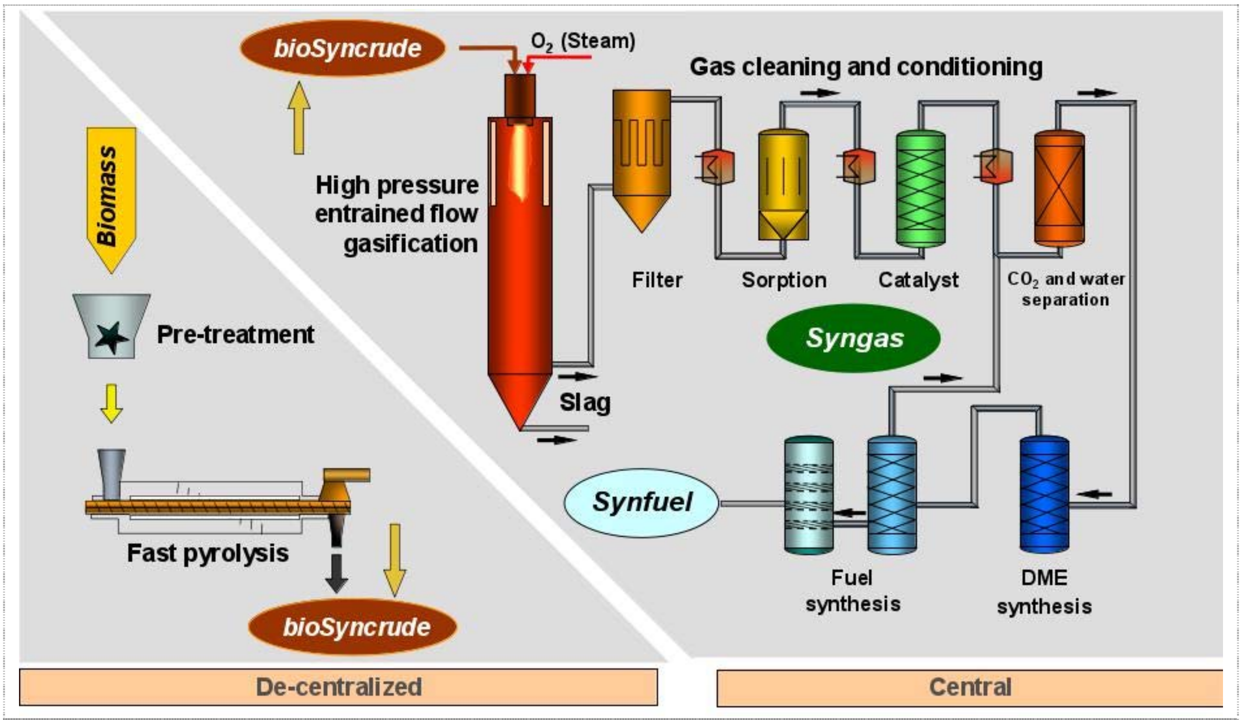

Figure 1: Schematic of the Bioliq process for production of synfuels from biomass (© KIT)[1]

The construction of the pilot plant was carried out in four subsequent stages, funded by the Federal Ministry of Food and Agriculture in Germany and by the state of Baden-Wuerttemberg. In the first one, which began in 2005, fast pyrolysis module (2 MW or 500 kg/h dry feedstock) was erected, being brought in operation in 2009[1]. In the second stage, the entrained flow gasifier (5 MW or 1 t/h biosyncrude) was realised in the period from 2010 until 2014[1]. Within the same period gas cleaning, methanol/dimethyl ether synthesis (third stage – 150 kg/h) and gasoline synthesis (fourth stage – 100 l/h) [1] were installed. First operation of the complete process was performed in 2014 with the production of synthetic gasoline from wheat straw. Since then the pilot plant was operated for further process development and optimization in test campaigns of typically several weeks duration. For operation, a dedicated team of engineers and operators is available, supported by researchers of the participating institutes of KIT. Fuel testing is currently conducted within the refuels project (www.refuels.de) by KIT and its partners from automotive industry.

As a research and development platform, the Bioliq® process is also in operation for research purposes with several KIT-internal and external partners. The Bioliq process chain was considered and evaluated, for example, the EU FP7 RNEW and BioBOOST projects and is now part of the national refuels project funded by the state of Baden-Wuerttemberg. It is linked to the Energy Lab 2.0 in direct neighborhood, providing bio-synthesis gas to produce other chemical energy carriers or to supply the micro-turbine, operated by DRL in cooperation.

The Power-to-Gas process consists in the conversion of “green” hydrogen provided by electrolysis and carbon dioxide into methane in a three step methanation process. The Power-to-Liquid process develops the production of synthesis gas from “green” hydrogen and carbon dioxide capture from the air, which is used in a Fischer-Tropsch reaction to produce e-fuels[4]. –Also, the synergetic combination of Btl with PtL fuel production can be verified within this combined infrastructure.

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period		2000-2004 Test in own and industrial process development units	2005 – 2013 Sequential series of projects, technologies selected specifically for high TRL	
Driving frame conditions (which policy frame and/or society pushed the R&D focus)			Use of decentral agriculture residues (valorisation), initiated by an own report in 1998, updated in 2003 [L. Leible et al., Energie aus biogenen Rest- und Abfallstoffen, Wissenschaftliche Berichte, FZKA 5882, 2003]	
R&D focus related to the technology itself		Work among the participating institutes on the key technologies fast pyrolysis and other liquefaction technologies, gasification and syngas chemistry for fuels and chemical production.	Scope of pilot plant operation is on flexibility in feedstock (specifically ash rich feedstock), process stability, dynamics and optimization and fuel conditioning	

R&D focus related to accompanying topic		Overall assessment of economic, ecological and social indicators, use of alternative feedstock (organic waste fractions), development of alternative and tailor-made fuels.	Cost assessment in comparison with other high-TRL processes	
Involved actors (from academia and industry) and their role			Air Liquide Global E&C Solutions (Gasifier, pyrolysis plant) CAC Chemieanlagenbau Chemnitz GmbH (gasoline and DME synthesis plant) MUT Advanced Heating GmbH (gas cleaning) Bauer AG (biosyncrude preparation) BAUER MAT Slurry Handling Systems (biosyncrude preparation) Calida Cleantech (hot gas filtration)	
Public funding? If yes, mentioned the program			Agency for Renewable Resources e. V. (FNR) and Ministry of Food and Agriculture (BMEL) European Union (EU), European Regional Development Fund (ERDF) and state of Baden-Württemberg (synthesis plant)	

Economic factors			Total investment: EUR 64,000,000[2]	
Driving factors for success			Bioliq® process configuration successfully verified Long term operation possible overcoming typical starting problems, room for various feedstock and process conditions optimization, Fuels were tested positively	
Lessons for other projects			Pilot projects need sufficiently long life time for construction, commissioning, start-up operation and operation. Budget need to be planned accordingly.	

Information on SDGs and esp. factors with regard to economics and environment

The project contributes to several Sustainable Development Goals, for example, to clean and affordable energy, production, sustainable consume, production, and industrial growth, climate protection. As a renewable fuel, the Bioliq products reduces the GHG emissions compared to fossil fuels. For the production of gasoline or Fischer-Tropsch hydrocarbons CO2 reduction potential above 80 % were found without further optimization in the EU RENEW and BioBOOST projects.

A specific feature of the Bioliq® concept is the combination of decentralized and central conversion sites, allowing to generate added value in agricultural and forest areas, but also to benefit from economy-of-scale in fuel production. With the fast pyrolysis decentralized step, the suppliers of feedstock can participate in added value creation, which contributes to the regional development. Direct and indirect effects by commercialization have not been evaluated so far, e.g. job creation or development of supply industry and economy. It is expected that the decentralized and central plants contribute in the same way as other thermal plants on communal (CHP, waste incineration plants) or on industrial level (chemical plants, refineries).

Due to the feedstock flexibility and usage of lignocellulosic residues, there is no requirement of principle structure changes feedstock supply by agriculture and forestry. Therefore Bioliq® process is replicable in national, but also international level, depending on the availability of the residual feedstock. It can be adjusted to the amount of feedstock and its supply logistics. In the BioBoost project, these effects have been investigated by simulation of the supply logistics and to optimize the overall production costs.

Further scale-up is required for commercial implementation. Fast pyrolysis may be scaled-up by a factor of 10 to 50. This should not be a problem, because fast pyrolysis for bio-oil production (not gasification fuels) is already state of the art in this order of magnitude. Also, the specific reactor and heat carrier system used hast been applied already in the fossil fuel sector, e.g., for coal pyrolysis, oil shale and refinery crude treatment. Gasification and fuel synthesis also require scale-up. For the latter, technology exists commercially and may be applied directly. The same is valid for gas cleaning and conditioning. High pressure entrained flow gasification may require an additional scale-up step in the 50 MW range. Principally, these types of gasifiers can be constructed in even ten time larger conversion capacity as realized for coal gasification.

Overall, the project represents a technical success. The drop-in fuels components produced by Bioliq® do not require technological changes/ adaptations (e.g. in filling stations, engines and driving customs) and is flexible to produce different types of fuels depending on the process configuration. For full renewable fuels, additional conditioning will be required, e.g. to reduce the aromatics content in gasoline production or to adjust the hydrocarbon product distribution in Fischer-Tropsch synthesis.

The consistent funding policy and cooperation with diverse partners are explanations for the success of the project, which brought the technologies considered up to TRL 7 as a complete process chain. However, for implementation, clear and stable political and economic frame conditions need to be installed before process development and market implementation headed by industrial partners will take place.

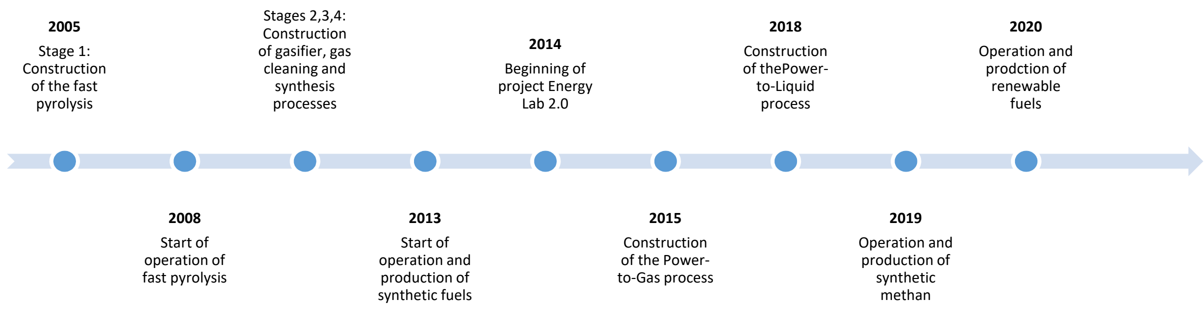

Figure 2: Timeline of the projects

Figure 3: The Bioliq demonstration plant at KIT (© KIT)

Info provided by:	Nicolaus Dahmen, KIT Gabriel de Paiva, Franziska Müller-Langer, DBFZ
More information:	1 https://www.bioliq.de/ 2 https://demoplants.bioenergy2020.eu/ 3 https://demoplants21.best-research.eu/uploads/relatedpublications/3240/3240_2015-10-25-074321_relatedpublications.pdf 4 https://www.elab2.kit.edu/bioliq.php

Annex: Further guidance *(delete this section in final factsheet)*

A “success story” is defined as a project that is implemented, is operating at scale, contributes to the UN Sustainable Development Goals (SDGs), has wide replicability and large scale-up potential.

Replicability and/or scale-up potential

R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	l
S	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	L

Sustainability: Relation to SDGs

SDG

	SDG	Description
☐	1 No poverty	End poverty in all its forms everywhere
☒	2 Zero hunger	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**
☐	3 Good health and well-being	Ensure healthy lives and promote well-being for all at all ages
☐	4 Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
☐	5 Gender equality	Achieve gender equality and empower all women and girls
☐	6 Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all
☒	7 Affordable and clean energy	**Ensure access to affordable, reliable, sustainable and modern energy for all**
☐	8 Decent work and economic growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
☐	9 Industry, innovation and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
☐	10 Reduced inequalities	Reduce inequality within and among countries
☐	11 Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient and sustainable
☒	12 Responsible consumption and production	**Ensure sustainable consumption and production patterns**
☒	13 Climate action	**Take urgent action to combat climate change and its impacts**
☐	14 Life below water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
☒	15 Life on land	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**
☐	16 Peace, justice and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
☐	17 Partnerships for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development

***Note: Bold text means** SDG is directly related to biomass*

IEA Bioenergy
Technology Collaboration Programme

Choren - Biomass gasification and Fischer-Tropsch synthesis

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

CHOREN Industries

CURRENT STATUS (2023)

Location:	Germany, Saxony, Freiberg
Technology:	Gasification of lignocellulosic feedstock, syngas cleaning/ conditioning and Fischer-Tropsch synthesis
Principle feedstocks:	Dry wood chips from recycled wood and residual forestry wood (Domestic feedstock)
Products/markets:	15,000 t/year FT liquids[13] Industrial facility was expected for 200,000 t/year FT liquids[9]
Technology Readiness Level (TRL):	TRL 6-7 – system prototype demonstration in operational environment[2]

SHORT DESCRIPTION

CHOREN Industries was proprietary of the Carbo-V® gasification process, which consists of a three-phase gasification to process woody biomass. Other feedstocks, as other biomasses (e.g. straw briquettes and miscanthus), plastics and municipal solid waste were also tested for gasification. The preparation of the feedstock requires the milling to particles less than 50 mm[12]. In the first phase, biomass with about 15-20% water content is gasified in a low temperature gasifier and forms char and gas rich in tar, the last one being further oxidized in the second phase, the high temperature gasification.

The last step consists in an entrained flow gasification, in which the raw syngas[10] is formed. The produced synthesis gas was cleaned/ conditioned and used in a Fischer-Tropsch reactor designed to produce long-chain hydrocarbons, resulting in a diesel like fuel. The conditioning is needed, as the raw syngas produced has a H_2/CO ratio of about 1, requiring a further water-gas-shift reaction to make it suitable for Fischer-Tropsch synthesis[12].

The company was developed for the thermochemical route with gasification and Fischer-Tropsch with core competence in gasification. It was established out of the former DBI after the German reunification (1990) and had already by April 2007 some 200 employees. They had strategic partners Daimler Chrysler and Volkswagen. The company was private with a partnership with Shell from 2005 (<25%) almost up to the point of bankruptcy. Capital employed by 2007 was more than €100 million. The company was located in Germany (Freiberg/Hamburg), China und USA[14].

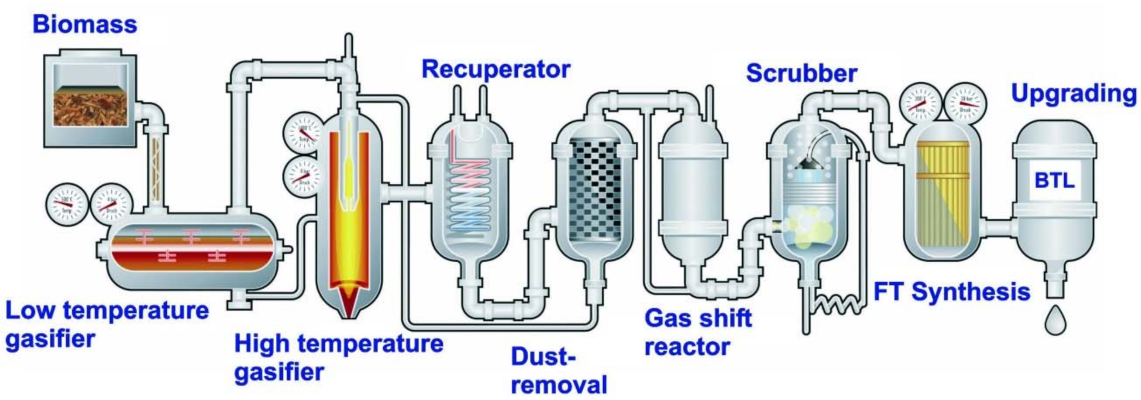

Figure 1: CHOREN process flowsheet (CHOREN®)[1]

The first pilot plant, called "Alpha", was built in 1997 in Freiberg (see Figure 2) and started up in 1998 to produce about 53 t/y FT Liquids (which corresponded a TRL of 4-5), reaching continuous operation, being in operation for around 17,000 hours[6]. Also, in Freiberg the process was scaled-up in 2002 in a "Beta" demonstration plant, planned to produce 15,000 t/y FT Liquids with start-up in 2009. The operation of the demonstration plant had a stepwise start-up, first beginning with the stable operation of the gasification system and afterwards integrating it with the Fischer-Tropsch system.

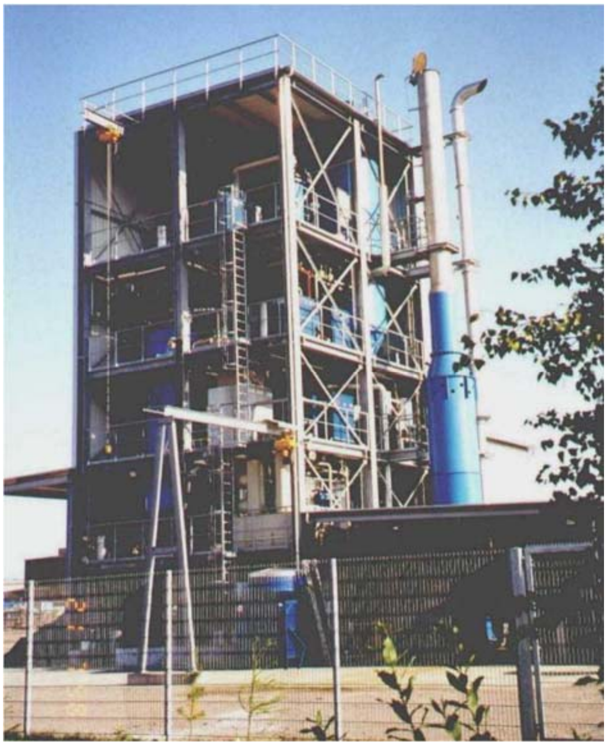

Figure 2: The Alpha CHOREN process plant (CHOREN®)[14]

The conclusions of CHOREN's evaluation were that a low hydrocarbon gas can only be achieved by entrained flow gasifiers. Classical entrained flow gasifiers only reach low efficiency and cannot be fed with solid biomass. The Carbo-V® process was therefore designed to increase efficiency via chemical quenching by blowing charcoal into hot gas decreasing losses in combustion chamber because of indirect cooling increase feedstock flexibility by transforming solid feedstock to gas and coal dust via autothermal pyrolysis (NTV)[14].

The results were absolute tar-free combustion or synthesis gases (no catalytic gas cleaning required). Low methane content even under 30 bar operation. High performance, efficiency of energy conversion of more than 80%. High flexibility in feedstock (all dry and carbon-containing feedstock possible). Conversion of ash to slag (granules suitable as a construction material). By the end of 2004 more than 17,000 operation hours were made in the Alpha plant.

All necessary approvals were submitted by the authorities. The biomass input system into the NTV was proven: A continuous and stable gas production in the NTV could be achieved. The whole charcoal conditioning and transport system was proven. Successful operation of the gasifier: Slagging of the wall of the combustion chamber. No damages on the lining. Some minor problems could be identified and solutions were developed[15].

During the early development the criteria[14] for the selection of a process for the production of syngas from biomass (gasification process) were:

- Gas quality
- Content of hydrocarbons (methane, tar,...) in raw gas
- H2 / CO ratio
- Impurities
- Cold gas efficiency
- Feedstock flexibility
- Operation under pressure
- Maximum power per unit / scalability
- Investment and operation costs.

The Alpha plant first produced methanol and the step into commercial process could have been take there. However, with the strategic partner of VW the aim was shifted for diesel, which is more complex and costly. It is evident that a complex process was added for an even more complex process, and demanding large scale for commercial success. Still an intermediate step was needed to prove the viability, the Beta plant.

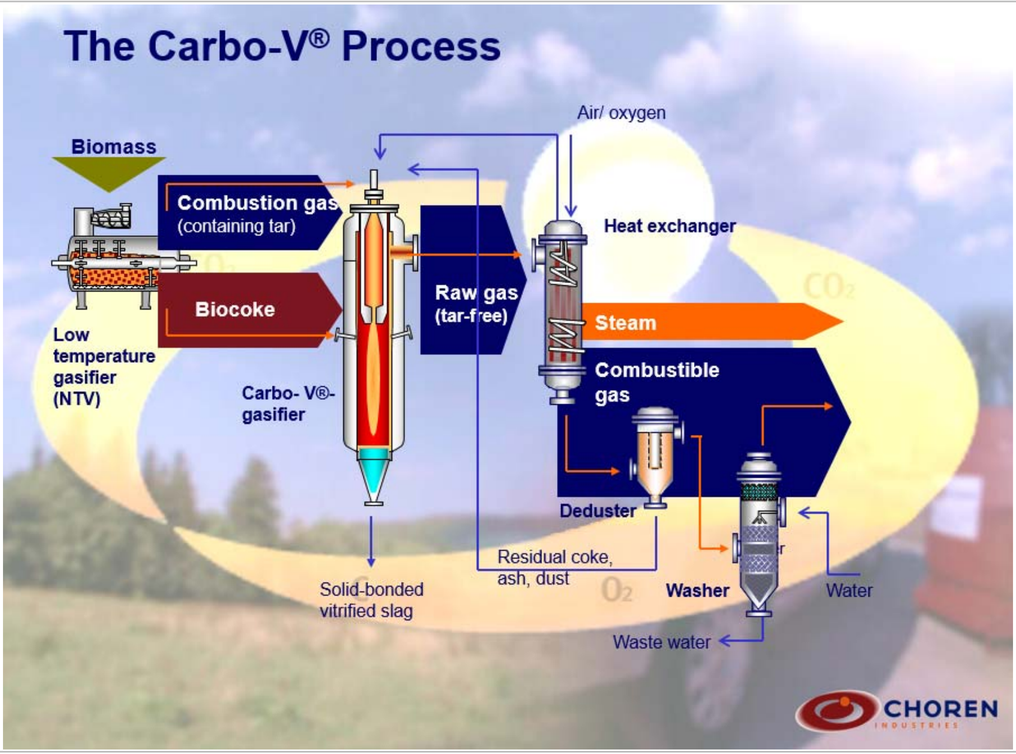

Figure 3: CHOREN core process flowsheet (CHOREN®)[14]

Milestones[14] included:

- 1997/98: Construction and commissioning of the Carbo-V® pilot gasification unit (1MW)
- 1998 - 01: Holistique experimentation program
- 2001: Demonstration of gas engine with clean wood gas
- 2002/03: Construction of the synthesis unit
- 2001 First BtL from bio-syngas in laboratory scale
- 13 April 2003: First liquids (methanol) from wood produced
- 6 May 2003: After the production of 11,000 liters, the R&D program for methanol was finished
- June 2003: First production of FT-liquids from wood
- 2004: Process and product optimization in the EU 6th frame program (RENEW).

The plan of the company was to further scale-up the BtL process in a “Sigma” plant in Schwedt for refinery integration and in Lubmin as a greenfield plant to produce up to 200,000 t/y each of FT liquids (TRL 8), but neither were realized as in 2011 the organisation filed insolvency[3]. For the production of the commercial scale, it was planned to utilise four parallel gasifiers with a capacity of 160 MW_{th} [9] each.

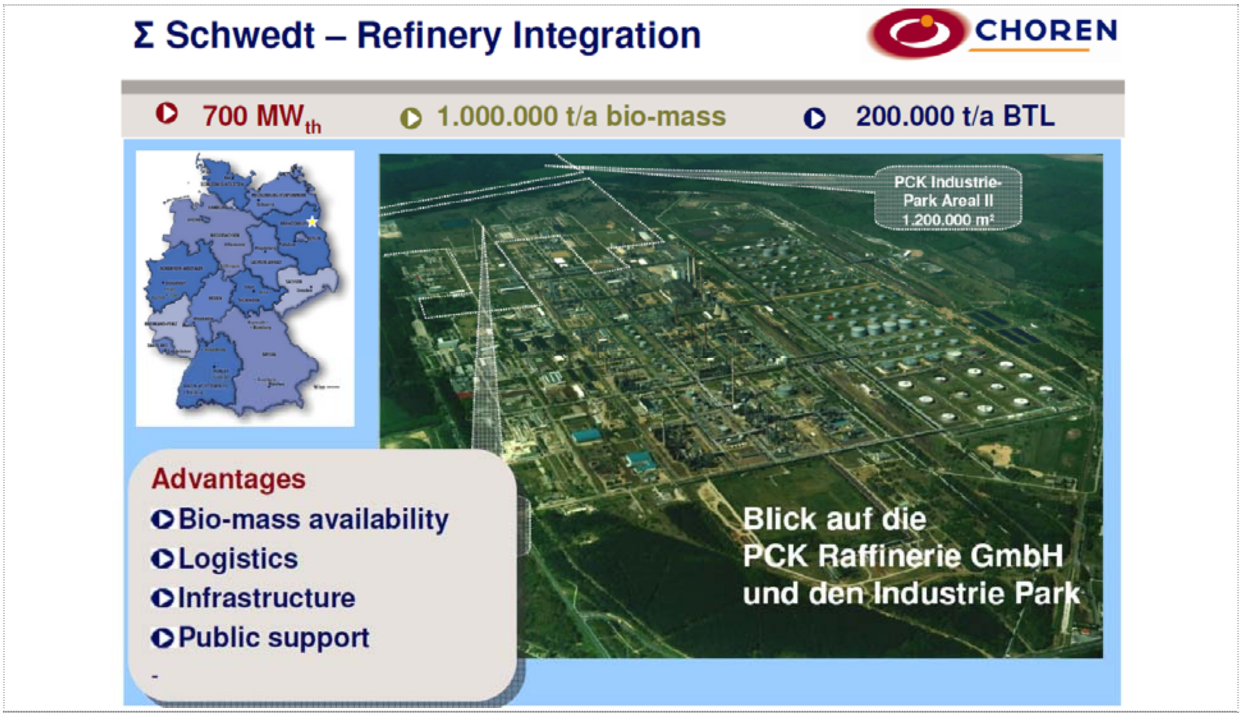

Figure 4: CHOREN Sigma plant description (CHOREN®)[15]

In 2012 Linde bought the patented gasification technology and industrialised for commercial deployment but costs and business conditions have not been favourable. Shell, the proprietary of the Fischer-Tropsch SMDS technology, utilized the synthesis technology firstly commercially in its refinery in Bintulu in 1993[9] and then in the Pearl GTL production plant in Qatar[3].

The concept of biomass gasification and FT synthesis is now underway with other developers and companies in Europe and the USA (like Fulcrum Bioenergy which is just now starting delivering products as of June 2023). As with many of the technologies, timing and market have been both keys to success and downfalls. Rarely, technologies have been proven not to work or operate satisfactory and the cause for hard lessons. Capital expenditure and not fast enough market penetration with plants being built have in many cases been the major downfall factors.

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period	<1998	1998 - 2002	2009 - 2011	Expected at 2012/13 (cancelled)
Driving frame conditions (which policy frame and/or society pushed the R&D focus)	Production of synthetic fuels as alternative to the fossil fuel sources[11].		Development of biomass-based synthetic fuel[11].	
R&D focus related to the technology itself	Development of Carbo-V gasification technology	Gasification and synthesis technologies coupling	Achievement of continuous operation	
R&D focus related to accompanying topic			Company estimated an 87% GHG emissions reduction compared to fossil production of diesel[6]	For the location of the industrial facility in Germany, 20 possible locations were identified for the erection of the first Sigma plant[9].
Involved actors (from academia and industry) and their role			CHOREN (Plant operation, gasification), Shell (Fischer-Tropsch and downstream technology), Daimler and Volkswagen (Fuel tests)[1]	
Public funding? If yes,				

mentioned the program				
Economic factors		CAPEX estimated to EUR 25.3 million and OPEX EUR 5.4 million (2009) for a facility processing 30 MWth feedstock and 10 MWe output[12]	For the semi-industrial facility, investments estimated to EUR 120 million (2010)[11]. Estimated investment over EUR 180 million (2010) to develop the technology[5]	For the commercial facility, it was expected to invest over EUR 800 million[9] in 2008
Driving factors for success			Capital-strong company owners and market readiness with valued product	
Lessons for other projects			Timing, extensive R&D at large plant scale with high monthly costs drains company resources	

Information on SDGs and esp. factors with regard to economics and environment

The feedstock flexibility for utilization of residual biomass implies in no competition with food production and land utilization for agriculture. Estimations of the technology provider was over 80% GHG reductions[4]. The produced fuel, named as SunDiesel®, was presented with the possible advantages of having a high cetane number and therefore would achieve better performance, as well as would reduce the exhaust emissions due to lack of aromatics and sulfur in its composition[4]. The cold gas efficiency of the process is estimated to be 81.4%, and the overall thermal efficiency 90.5%[12].

In 2009 CHOREN reported having 260 employees[5], but the company filed insolvency in 2011[4]. Of one the factors for the insolvency is the financial difficulties to start-up the new plant in Freiberg[7]. It was expected that the commercial facility would employ about 850 people, divided into production (200) and biomass supply (600-700)[9].

The Biomass-to-Liquid technology has international level replicability, depending on the availability of feedstock. Also, the modular system makes it viable to design the process according to the needs of the specific location[12]. Furthermore, the gasification system can be coupled with other synthesis systems and is not limited to Fischer-Tropsch synthesis. Indeed, the company made tests in 2003 for production of methanol[9] and was analysing the possibility to produce hydrogen[11].

The project can be described as a technical success. The products of the process do not require technological changes/ adaptations (e.g. in filling stations, engines and driving customs) and was able to be scaled up to TRL 6-7, although there were no further incentives to further scale-up the technology and reduce its costs. It is mentioned that the lack of policy support and investment contributed to the stop in the scale-up of the technology[7].

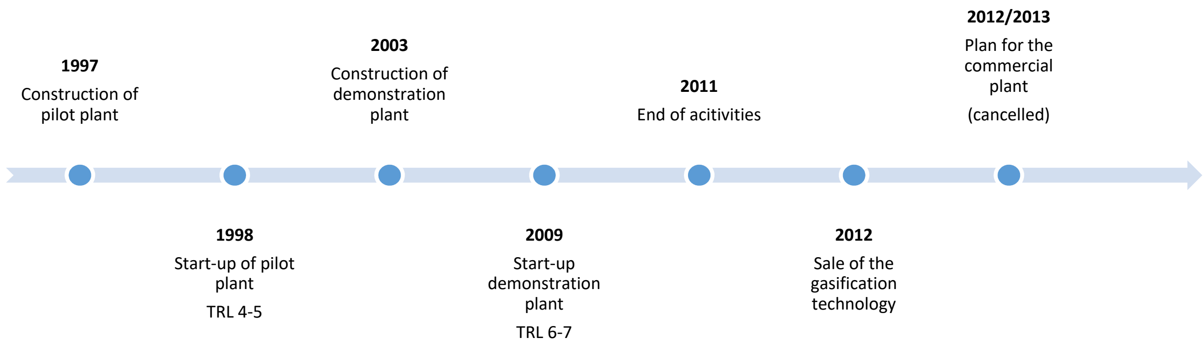

Figure 5: Timeline of the projects

Figure 4: Pilot production plant of CHOREN in Freiberg (CHOREN®)[1]

Info provided by: Gabriel de Paiva, Franziska Müller-Langer, Tomas Ekbom, Review by former CHOREN employees

More information:

1 https://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/presentations/CHOREN-Purdue-May2008.pdf

2 https://demoplants.bioenergy2020.eu/

3 https://www.etipbioenergy.eu/value-chains/conversion-technologies/advanced-technologies/biomass-to-liquids/discontinued-btl-projects

4 https://www.etipbioenergy.eu/images/Matthias_Rudloff.pdf

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6 https://www.nrel.gov/docs/fy11osti/50441.pdf

7 Ioanna Dimitriou, Harry Goldingay, Anthony V. Bridgwater, Techno-economic and uncertainty analysis of Biomass to Liquid (BTL) systems for transport fuel production, Renewable and Sustainable Energy Reviews, Volume 88, 2018, Pages 160-175, ISSN 1364-0321

8 http://www.globalbioenergy.org/uploads/media/0805_E4tech_-_Advanced_technologies.pdf

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13 https://juser.fz-juelich.de/record/135494/files/HP4b_2_Vogels_rev0604.pdf

14 Rudloff, M., "Operation experiences of Carbo-V process for FTD production" SYNBIOS – Second Generation Automotive Biofuel Conference, Stockholm, 18-20 May 2005

15 Rudloff, M., "First Commercial BTL Production Facility - The Beta Plant Freiberg", SYNBIOS II, Stockholm, 23-24 May, 2007

Annex: Further guidance *(delete this section in final factsheet)*

A “success story” is defined as a project that is implemented, is operating at scale, contributes to the UN Sustainable Development Goals (SDGs), has wide replicability and large scale-up potential.

Replicability and/or scale-up potential

R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	l
S	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	L

Sustainability: Relation to SDGs

SDG

- ☐ End poverty in all its forms everywhere
- ☒ **End hunger, achieve food security and improved nutrition and promote sustainable agriculture**
- ☐ Ensure healthy lives and promote well-being for all at all ages
- ☐ Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
- ☐ Achieve gender equality and empower all women and girls
- ☐ Ensure availability and sustainable management of water and sanitation for all
- ☒ **Ensure access to affordable, reliable, sustainable and modern energy for all**
- ☒ Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- ☒ Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- ☐ Reduce inequality within and among countries
- ☐ Make cities and human settlements inclusive, safe, resilient and sustainable
- ☒ **Ensure sustainable consumption and production patterns**
- ☒ **Take urgent action to combat climate change and its impacts**
- ☐ Conserve and sustainably use the oceans, seas and marine resources for sustainable development
- ☒ **Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**
- ☐ Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
- ☐ Strengthen the means of implementation and revitalize the global partnership for sustainable development

***Note: Bold text means** SDG is directly related to biomass*

IEA Bioenergy
Technology Collaboration Programme

Chemrec® - Black liqour gasification with motor fuels

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

Chemrec AB / LTU Green Fuels

CURRENT STATUS (2023)

Location:	Sweden, Piteå at Kappa Kraftliner Pulpmill by LTU GreenFuels
Technology:	20 tonnes DS (Dry Solids) per day (ca 3 MWth), high-pressure, oxygen-blown entrained-flow gasification of black liquor with chemical recovery for green liquor, gas cleaning/conditioning and methanol/dimethyl-ether synthesis.
Principle feedstocks:	Black liquor feedstock (in the project was also used pyrolysis liquids from biomass as co-feed, the technology is applicable to diverse feedstock). Black liquor is a by-product in chemical pulp mills, whereas pyrolysis liquids can be produced elsewhere.
Products/markets:	The products have been more than 1000 tonnes bio-DME and in addition more than 50 tonnes raw biomethanol for testing purposes. The DME and methanol has been used in field tests by partners Volvo Trucks, Flogas and Perstorp. The process can be changed to produce other transport fuels (e.g. diesel, kerosene) and also platform chemicals[2]. A next scale-up would reach plant size with capacity of 150,000 tonnes of biomethanol or 100,000 tonnes of bio-DME per year.
Technology Readiness Level (TRL):	TRL 6-7 – system prototype demonstration in operational environment[2]

SHORT DESCRIPTION

Gasification of black liquor is an alternative recovery technology that has gone through a step-wise development since its early predecessor was developed in the 1960s. The currently most commercially advanced Black Liquor Gasification (BLG) technology is the CHEMREC® technology, which is based on entrained-flow gasification of the black liquor at temperatures above the melting point of the inorganic chemicals. In a BLG system, the recovery boiler is replaced with a gasification plant. The evaporated black liquor is gasified in a pressurised reactor. The generated gas is separated from the inorganic smelt and ash. The smelt falls into the quench bath where it dissolves to form green liquor in a manner similar to the dissolving tank of a recovery boiler. The raw fuel gas exits the quench and is further cooled in a counter-current condenser[3].

Hydrogen sulphide is removed from the cool, dry fuel gas in a pressurised absorption stage. The resulting gas is a nearly sulphur-free synthesis gas (syngas) consisting of mostly carbon monoxide, hydrogen and carbon dioxide. The gas can then be utilized for biofuels production after gas treatment and conditioning. The synthesis gas is cleaned and conditioned to head to the methanol or dimethyl ether (DME) synthesis, which is used as basis for the fuel synthesis (e.g. gasoline like fuel)[5].

The Black Liquor Gasification with Motor Fuels production (BLGMF) system is an alternative for processing black liquor and is intended to replace the conventional recovery boiler. The pressurised, oxygen-blown Chemrec system provides a totally new approach for the recovery of chemicals and energy for chemical pulping processes. A schematic drawing of the BLGMF system is shown in Figure 1. The gasifier/quench system is analogous to the recovery boiler system in the respect that it converts black liquor into green liquor. The BLGMF system partially converts (gasifies) the liquor with oxygen to produce a synthesis gas and a molten salt smelt. The gas and smelt are cooled and separated in the quench zone below the gasifier. The smelt falls into the quench bath where it dissolves to form green liquor in a manner similar to the dissolving tank of a recovery boiler.

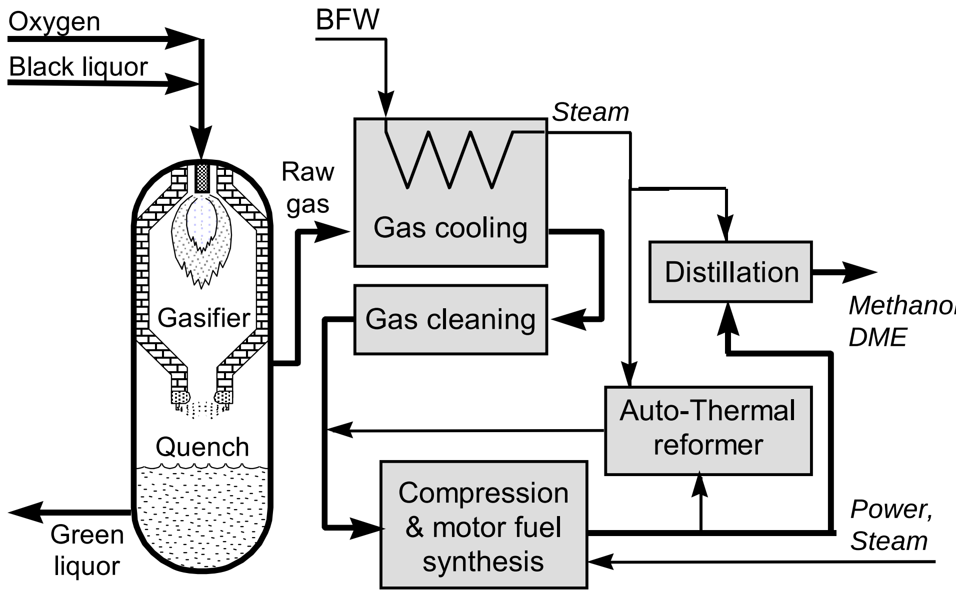

Figure 1: Chemrec black liquor gasification process integrated with methanol/DME synthesis (© Chemrec)[2]

In the case of methanol production with this process scheme, almost 70% of the extra biomass energy is transformed to methanol (or DME), giving an exergy efficiency about twice that of a recovery boiler system. The extraordinary methanol/DME output of a black liquor motor fuel system offers the potential to significantly reduce fossil fuels used for transport. In short, "green" methanol/DME from biomass and black liquor replaces fossil fuel-based energy.

In 1997 a demonstration program was initiated in Sweden with €26.4 million provided by the Swedish Energy Agency. The development was focused on demonstrating at development plant level and a plant was built with operation in 2001 in Piteå, Sweden at the adjacent pulp mill. Thereafter, the plant was complemented with integrated methanol/DME production including extensive deep gas cleaning with the Bio-DME project. The plant was started in 2005 and operated for more than 12,000 hours in full integration mode.

The operation experience is summarized as:

- Atmospheric air-blown gasification: pilot plant during 1991-1994 and, first commercial plant at Weyerhaeuser in New Bern, USA. 45 MWth / 47,000 h of operation between 1995 and 2008[2]
- Pressurized, oxygen-blown gasification: pilot plant during 1995-1997 and, first development plant 3 MWth / 30 bar / in Piteå, Sweden with >28,000 h of operation[2].

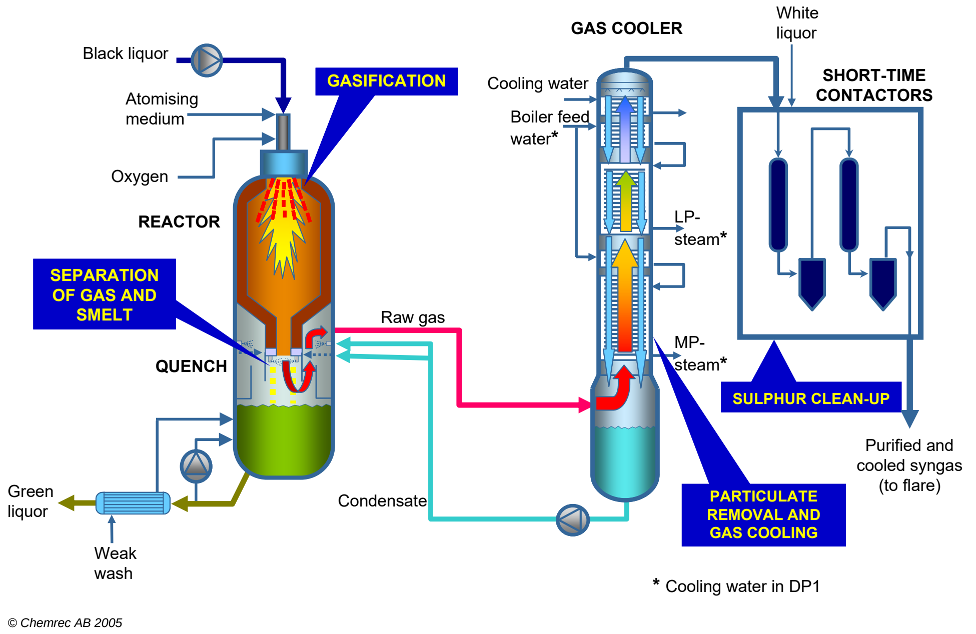

Figure 2: Illustration of the core Chemrec process in Piteå, Sweden, for pure syngas. (© Chemrec)[1]

In parallel with a verification program and further testing and operation a commercialization program for full-scale production plant was made with several projects where one being the Domsjö Fabriker project for 150,000 tonnes methanol at Örnsköldsvik. Other projects were focusing on techno-economic studies where the feasibility with different process integrations for synthesis of e.g. Fischer-Tropsch diesel and biojet and lubricants as products. See images of made-up plant visualization in Figure 3.

Figure 3: Drawings of proposed full scale plant for biofuels production. (© Chemrec)[1]

Latest development have included testing of co-gasification of pyrolysis-derived liquids from biomass and development for an extension of the plant for biojet production as step 1 in the commercialization for full-scale production plant. See Figure 4 for the proposed steps.

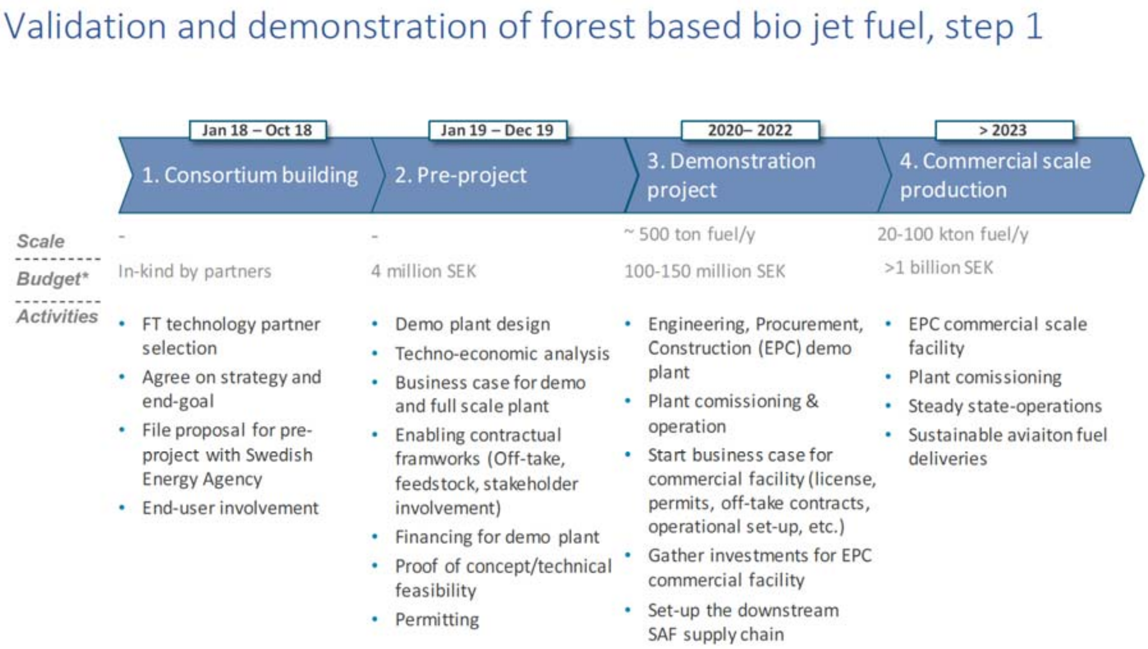

Figure 4: Planned commercial development for biojet production (© Luleå Green Fuels)[10]

The plant has been idle and on-hold for couple of years but in 2023 there is new development for this to be started as a new investor has entered and some €10 million secured from EU justification funds[14]. The pilot plant is owned by Luleå Technical University in the company LTU Green Fuels and will deliver large-scale testing of technologies in hydrogen.

Figure 5: The Chemrec development demonstration plant at Piteå (© Chemrec)[2]

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period	The technology was acquired from Kvaerner Pulping which had already completed this level	The technology was acquired from Kvaerner Pulping which had already completed this level	2005 – 2013, 2013 - 2023	
Driving frame conditions (which policy frame and/or society pushed the R&D focus)			Business development in the pulp industry and tax exemption of clean biofuels. Understanding process chemistry and materials	
R&D focus related to the technology itself			Verification and process parameters testing with material technology for stable operation	
R&D focus related to accompanying topic			Scope of pilot plant operation is on flexibility in feedstock (specifically ash rich feedstock), process stability, dynamics and optimization and fuel conditioning	
Involved actors (from academia and industry) and their role			Luleå Technical University Volvo Trucks (DME testing) AGA Linde AG (gases)	

			Haldor Topsoe (synthesis) Smurfit Kappa Kraft (pulp mill) ETC (lab and testing)	
Public funding? If yes, mentioned the program		Yes	Demonstration program of Swedish Energy Agency	
Economic factors			Total investment estimated: More than EUR 80,000,00[2]	
Driving factors for success			Chemrec® process configuration successfully verified Long term operation possible overcoming typical starting problems, room for various feedstock and process conditions optimization, Fuels were tested positively	
Lessons for other projects			Steering instruments needed with government guarantees for bankable project for project financing to achieve TRL 8.	

Information on SDGs and esp. factors with regard to economics and environment

The project contributes with the Sustainable Development Goals, seen that the residual biomass from pulp industry does not compete with food/ land use. Furthermore, it reduces the GHG emissions compared to fossil fuels. In addition it co-processing of pyrolysis liquids give a specific feature to the combination of decentralized and central conversion sites, allowing to generate added value in agricultural and forest areas, but also to benefit from economy-of-scale in fuel production.

With the fast pyrolysis decentralized step, the suppliers of feedstock can participate in added value creation, which contributes to the regional development. Direct and indirect effects by commercialization have not been evaluated so far, e.g. job creation or development of supply industry and economy. It is expected that the decentralized and central plants contribute in the same way as other thermal plants on communal (CHP, waste incineration plants) or on industrial level (chemical plants, refineries).

With the collecting of wood chips from forest industry to pulp & paper manufacturing, the suppliers of are restricted to pulp mills having black liquor feedstock but bring development to regional forest owners and pulp producers. The production plant also contributes locally, employing engineers, mechanics and electricians for the operation. Because of the criteria for feedstock the process is not readily replicable in all international levels, but for regions with pulp industry. The plants are for integration and have scalability, depending on the availability of the residual feedstock.

Chemrec has demonstrated the world's only black liquor gasification plant for biofuel production to bio-DME. Planned commercial large-scale project on hold with EUR 350 million investment at Domsjö Fabriker AB for 100,000 tonnes bio-DME /140,000 tonnes bio-methanol per year from Chemrec gasification of cooking liquor. The project included: Detailed feasibility, budget quotes, environmental impact assessment, off-take term, EPC customary guarantees, and Industrial co-investors LOI with EUR 145 million pledged and EU approved 55 million EUR Swedish Energy Agency grant – still no go-ahead.

Extensive technology verification with >28,000 hours of gasification operation, of which >12,000 hours methanol/bio-DME production operation. Plant taken over by LTU Green Fuels, currently on idle with previous operation in campaign and for testing. Driving factors for success for a commercial plant: Strong, stable and long terms (beyond 2030) policies to give confidence to investors. The key condition required is the implementation on an EU and national level of long- term (at least 15 years) stable directives and regulations, which impact project cash flow, such as incentives and taxes.

Overall, the project represents a technical success. The fuels produced were also tested in new DME trucks with extensive fleet for 100,000 km driving each vehicle. In addition, the process could be used for synthesis to other fuels which do not require technological changes/ adaptations (e.g. in filling stations, engines and driving customs).

The consistent capitalisation into a company with selected owners, which are stakeholders and involving the industry and academia are explanations for the success of the project, which brought technologies up to TRL 7, developing various processes such as BLG. Furthermore, biofuels policy contributed to the driving force.

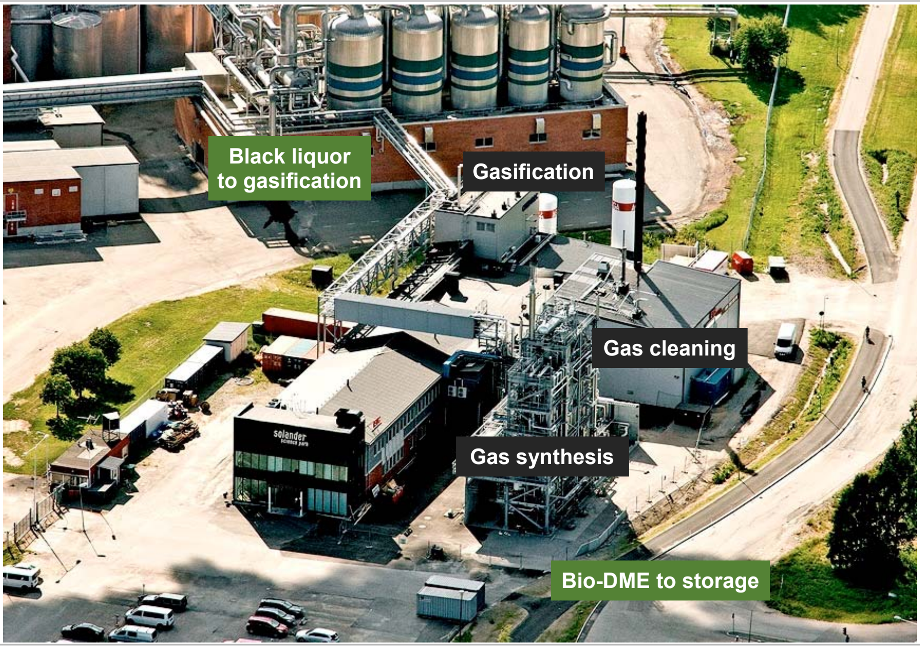

Figure 6: The Chemrec development demonstration plant with DME plant at Piteå (© Chemrec)[5]

Info provided by: Tomas Ekbom

More information: www.chemrec.se

1. Ekbom, T., Berglin, N., Lögdberg, S., "Black Liquor Gasification with Motor Fuel Production – BLGMF II", Swedish Energy Agency, FALT Program Report, Contract No. P21384-1, Stockholm, 2006

2. Ekbom, T., Lindblom, M., Berglin, N., Ahlvik, P., "Technical and Commercial Feasibility Study of Black Liquor Gasification with Methanol/DME Production as Motor Fuels for Automotive Uses – BLGMF", Swedish Energy Agency and European Commission, Altener II Report, Contract No. 4.1030/C/01-087, Stockholm, 2003

3. Ekbom, T., Berglin, N., Lögdberg, S., "High Efficient Motor Fuel Production From Biomass via Black Liquor Gasification", The 15th International Symposium on Alcohol Fuels, ISAF XV, San Diego, USA, 26-28 September 2005

4. Ekbom, T., Berglin, N., Lindblom, M., Ahlvik, P., "Cost-competitive, Efficient Bio-methanol/Bio-DME Production from Biomass via Black Liquor Gasification as Renewable Motor Fuels for Automotive Uses", 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, 10-14 May 2004

5. Ekbom, T., Berglin, N., Lindblom, M., Ahlvik, P., "Technical and Commercial Feasibility Study of Black Liquor Gasification with Methanol/DME Production as Motor Fuels for Automotive Uses - BLGMF", Energitinget 2004, Eskilstuna, Sweden, 9-10 March 2004

6. Ekbom, T., Berglin, N., Lindblom, M., "High Efficiency Methanol/DME Production from Biomass via Black Liquor Gasification as Renewable Motor Fuels", International Nordic Bioenergy 2003 Conference, Jyväskylä, Finland, 3-5 September 2003

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9. Ekbom, T., Berglin, N., Lindblom, M., "Feasibility and Market Potential of Black Liquor Gasification with Methanol/DME Production as Renewable CO2 Neutral Motor Fuels", The 14th International Symposium on Alcohol Fuels, ISAF XIV, Phuket, Thailand, 12-15 November 2002

10. Granberg, F., Biojet Biojet Demo Validation project, Luleå 2018

Annex: Further guidance *(delete this section in final factsheet)*

A “success story” is defined as a project that is implemented, is operating at scale, contributes to the UN Sustainable Development Goals (SDGs), has wide replicability and large scale-up potential.

Replicability and/or scale-up potential

R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☐	**H**	☒	**H**	☒	**h**
	☐	**M**	☐	**M**	☐	**m**
	☐	**L**	☐	**L**	☐	**l**
S	☐	**H**	☒	**H**	☒	**h**
	☐	**M**	☐	**M**	☐	**m**
	☐	**L**	☐	**L**	☐	**L**

Sustainability: Relation to SDGs

SDG

☐ 1 NO POVERTY — End poverty in all its forms everywhere

☒ 2 ZERO HUNGER — **End hunger, achieve food security and improved nutrition and promote sustainable agriculture**

☐ 3 GOOD HEALTH AND WELL-BEING — Ensure healthy lives and promote well-being for all at all ages

☐ 4 QUALITY EDUCATION — Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

☐ 5 GENDER EQUALITY — Achieve gender equality and empower all women and girls

☐ 6 CLEAN WATER AND SANITATION — Ensure availability and sustainable management of water and sanitation for all

☒ 7 AFFORDABLE AND CLEAN ENERGY — **Ensure access to affordable, reliable, sustainable and modern energy for all**

☐ 8 DECENT WORK AND ECONOMIC GROWTH — Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

☐ 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE — Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

☐ 10 REDUCED INEQUALITIES — Reduce inequality within and among countries

☐ 11 SUSTAINABLE CITIES AND COMMUNITIES — Make cities and human settlements inclusive, safe, resilient and sustainable

☒ 12 RESPONSIBLE CONSUMPTION AND PRODUCTION — **Ensure sustainable consumption and production patterns**

☒ 13 CLIMATE ACTION — **Take urgent action to combat climate change and its impacts**

☐ 14 LIFE BELOW WATER — Conserve and sustainably use the oceans, seas and marine resources for sustainable development

☒ 15 LIFE ON LAND — **Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**

☐ 16 PEACE, JUSTICE AND STRONG INSTITUTIONS — Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

☐ 17 PARTNERSHIPS FOR THE GOALS — Strengthen the means of implementation and revitalize the global partnership for sustainable development

***Note: Bold text means** SDG is directly related to biomass*

IEA Bioenergy
Technology Collaboration Programme

Gobigas - Biomass gasification and methanation

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

Göteborg Energi

CURRENT STATUS (2023)

Location:	Göteborg, Sweden
Technology:	Biomass gasification with, syngas cleaning/ conditioning and methane synthesis
Principle feedstocks:	Wood pellets and dry wood chips from recycled wood and residual forestry wood (Domestic feedstock)
Products/markets:	20 MWth bio-CNG (methane) as transport fuel[13] Industrial facility was expected for combined 100 MWth bio-SNG[9]
Technology Readiness Level (TRL):	TRL 7 – system prototype demonstration in operational environment[2] (gasification) TRL 8 – system complete and qualified (methanation)

SHORT DESCRIPTION

GoBiGas, which stands for Gothenburg Biomass Gasification Project, is part of Göteborg Energi's (Gothenburg Energy) investment in reducing the use of fossil fuels. The purpose of the project was for commercial-scale demonstration of the possibilities of gasification technology and to build a biogas plant for a methane product of Bio-CNG quality. The idea of the project was to contribute to the transition to more sustainable energy production and invest in an infrastructure investment that should be profitable in the long run.

The project began in 2005 with the goal of building a 100 MWth gas plant. However, the technology maturity was lower than the project expected. Therefore, it was decided in 2007 that the project would be divided into two stages, a research and demonstration plant of 20 MWth which in a next step will be supplemented with a commercial plant of 80 MWth. With the board's investment decision on 16 December 2010, the project entered the implementation phase. Stage 1 was expected to be completed in the spring of 2013.

The plant featured biomass gasification and methanization technologies with a first-of-its-kind tested in commercial facilities of this scale. This placed technology development such as procurement and cooperation with suppliers. The plant was procured as EPC with Metso Power with Repotec as technology supplier for gasification and EPCM with Jacob Process and Haldor Topsoe for gas cleaning and methanation and utilities.

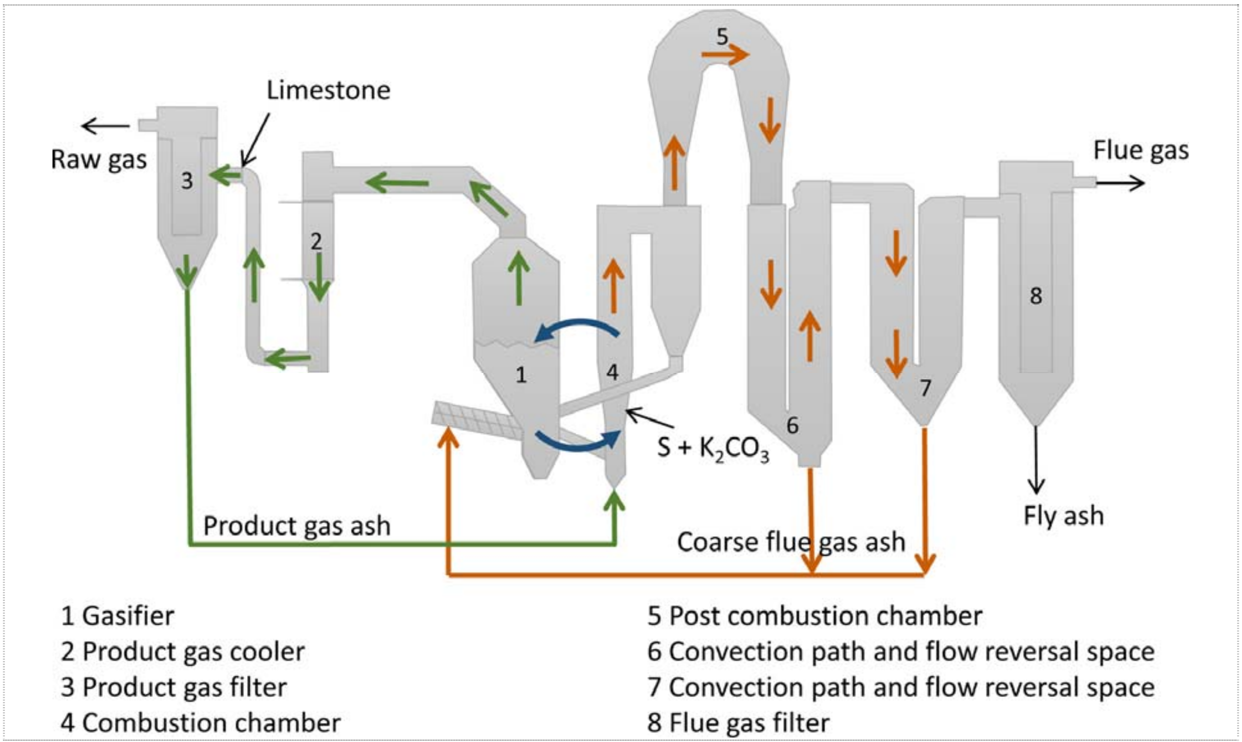

Figure 1: The Repotec in-direct gasification technology process scheme (Chalmers)[2]

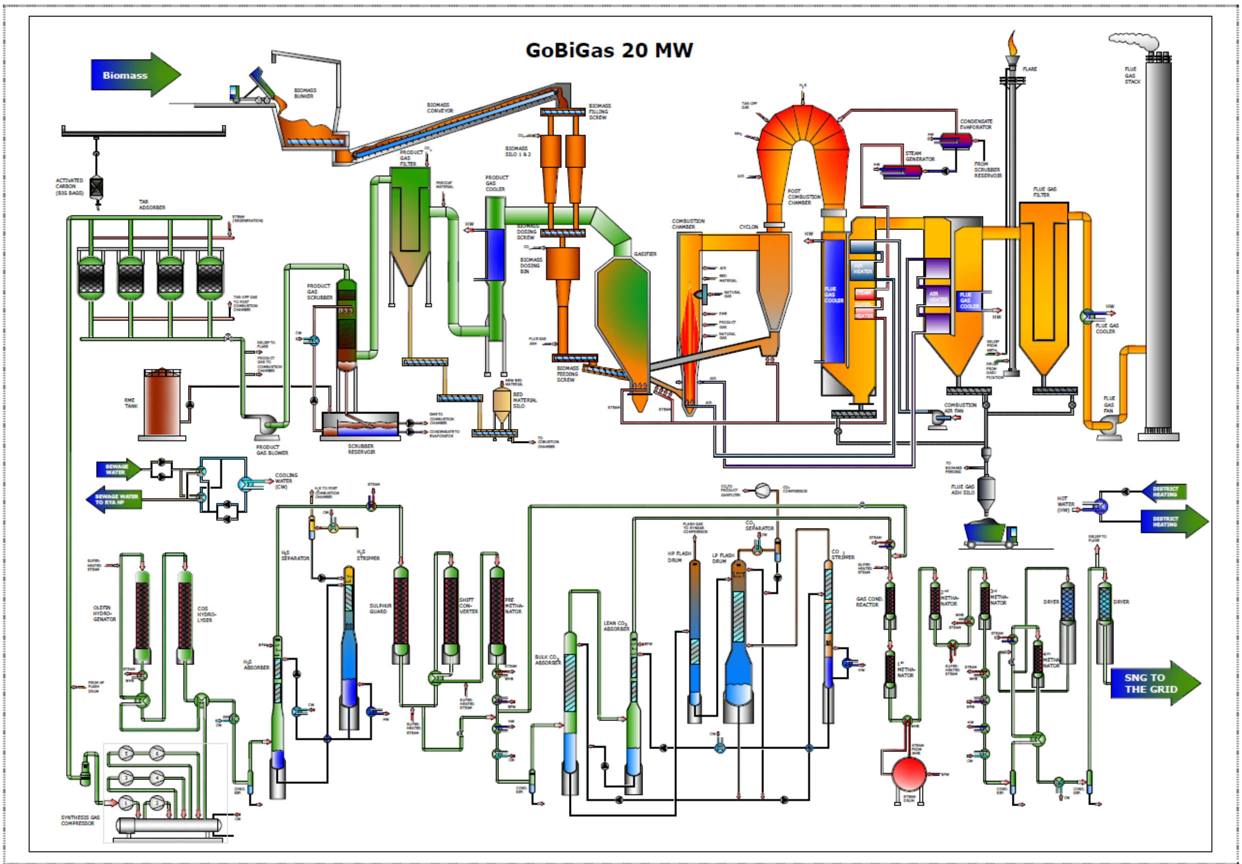

Figure 2: The GoBiGas process flowsheet (Chalmers)[2]

The process starts with biomass feeding into Indirect Circulating Fluidized Bed Gasification with Removal of light tar. The flue gases in the Combustion reactor which provides the heat necessary in the gasification are taken to the Flue gas train. The product gases is led to Gas cooling, removal of particles and tar. Then Hydrogenation of olefins and COS followed by H_2S scrubber and next steps of Pre-methanation, CO_2 scrubber, Methanation which is where the synthesis is made of the syngas. The end product is taken to Drying and compression for injecting to fossil gas grid or delivered as compressed gas.

In order to procure a plant an evaluation was made into different biomass gasification technologies. The focus was for methane where in-direct gasification has an inherent advantage with significant methane share already in the product gas and the reaction occurs at atmospheric pressure. The disadvantages are an efficient methanation can occur of syngas downstream and that direct biomass gasification technologies can be pressurized adding capacity at same reactor scale. Therefore, the development was chosen for modular stages.

The project had thus two phases:

- 20 MW Biomethane
  (32 MW fuel, 6 dry ton biomass/h)

- 80 – 100 MW Biomethane
  (125-150 MW fuel 25-30 dry ton biomass/h)

Phase 1, demonstration, to build experience for Phase 2, the second commercial phase, possibly with three reactors of same size as phase 1. As can be seen in Figure the plants that had been built were at most small and not of any large-scale. Should the project have chosen a direct gasification technology a single reactor could have been 100-200 MWth and the need for several phases or reactors not needed. However, such a plant would entail substantially more capital cost and with the inherent risk for a first-of-its-kind a too big and bold of a step. Still, the chance for a cost-competitive plant was surely higher as large-scale would have been accomplished in just one phase. The decision is not straight-forward and other aspects are also essential.

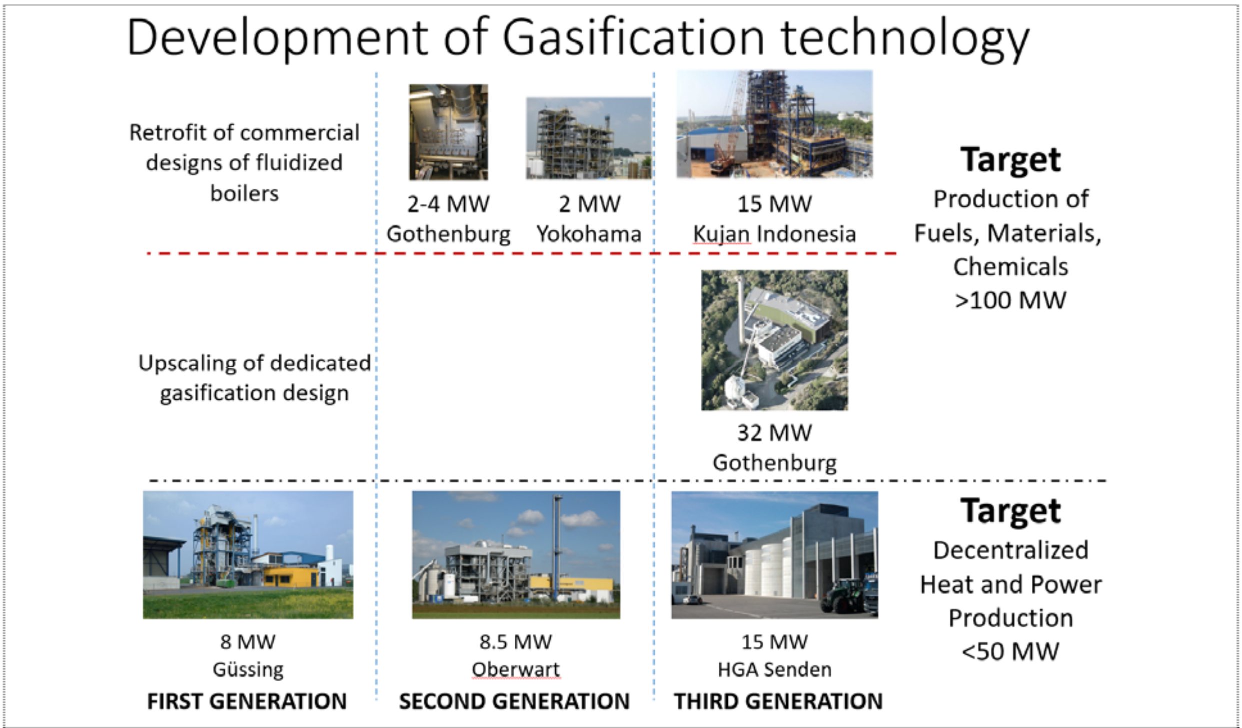

Figure 3: Development of in-direct biomass gasification technology (Chalmers)[2]

The location of the facility in the Rya area in Gothenburg is advantageous because of the access to developed infrastructure in terms of connection to electricity, gas and district heating networks and conditions for fuel transport by boat and train. The proximity to Chalmers University of Technology, where research in gasification technology is ongoing, is also an advantage. The project received good response and good publicity from various external stakeholders and both authorities, interest organisations, suppliers and future customers followed the project with great interest.

Accomplishments include first in the world for high quality biomethane from biomass through gasification. First Swedish plant to inject biomethane into the national grid. Performance goals of demonstration were a biomass to biomethane yield of ≥65 % and biomass to energy efficiency of ≥90 % and 8,000 hours continuous operation per year.

The evaluation of the project on behalf of the owners gave that Phase 1 could not be profitable as a stand-alone plant unless the price of gasoline would rise to SEK 25/liter in real terms (2009). The probability of profitability would increase if phase 2 is built but the investment calculation is uncertain as there are no complete cost estimates. An estimate points to at least SEK 2,500 million for phase, but that could be higher. The total investment to build both phases would thus exceed SEK 3,700 million. At present, there is a strategic decision from the board that the company should focus on production of biogas through gasification, but the company has not designed and evaluated differently options for financing of phase 2 and thus is not included in the business investment plan.

Conclusions and lessons learned were that demonstration met all pre-set performance goals and made the technology ready for commercial implementation. Demonstration provided vital information on how to operate the gasification section in an industrial scale. The demonstration plant could not reach commercial break-even 2018 and was therefore mothballed. In the autumn of 2021 the disassembly of the plant began.

Overall, the time of operation has been a technical success and all process steps functioned in integration mode with a few technical issues like control of the gasification process, tar deposits, potassium deposits. As a statement plant this has showed the viability of the concept and that biomass can be converted into bio-CNG to replace fossil fuels and operated like any other commercial high availability chemical production plant. This is a major feat in its own.

Lastly, taking into consideration of security of supply of renewable gas in Sweden, security of cost from spiking fossil gas prices and electricity prices there are several benefits of strategic value which have been evident last year with the Russian invasion of Ukraine and which was not accounted for when the project was started or the decision for dismantling. Timing is sometimes said to be everything.

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period			2007 - 2015	Expected at 2020 (cancelled)
Driving frame conditions (which policy frame and/or society pushed the R&D focus)			Tax exemption of biofuels Development of biomass-based synthetic gas[1].	
R&D focus related to the technology itself			Achievement of continuous operation, process parameters	
R&D focus related to accompanying topic				
Involved actors (from academia and industry) and their role			Metso Power as EPC Repotec (gasification) Jacobs (utilities) as EPCM Haldor Topsoe (gas cleaning, methanation)	
Public funding? If yes, mentioned the program			825 million SEK (EUR 76 million)	

Economic factors			For phase 1 the estimated cost is some 1500 million SEK (EUR 130 million) but the first estimate was 800 million SEK[1]	For the commercial facility in second phase, it was expected to invest over 2500 million SEK (EUR 220 million[2])
Driving factors for success			Capital-strong company owners and market readiness with valued product	
Lessons for other projects			Defining and achieving the competitiveness of the project, understanding complexity of procurement, and communicating performance goals and set targets.	

Information on SDGs and esp. factors with regard to economics and environment

The feedstock flexibility for utilization of residual biomass implies in no competition with food production and land utilization for agriculture. The produced fuel, renewable methane was of Bio-CNG quality and used as motor fuel, and also supplied to customers in the gas pipeline of the Swedish west coast.

The project can be described as a technical success. The products of the process do not require technological changes/ adaptations (e.g. in filling stations, engines and driving customs) and was able to be scaled up to TRL 7-8, although there were no further incentives to further scale-up the technology and reduce its costs. It is mentioned that the lack of policy support and investment contributed to the stop in the scale-up of the technology[7].

Figure 4: GoBiGas *production plant in Gothenburg (Chalmers)*[2]

Info provided by:	Tomas Ekbom
More information:	1 Söderberg, A., Hammarskjöld, D., Nilsson, M., ”Genomlysning av projekt GoBiGas, Göteborg”, Göteborg Stad, 2012 2 Thunman, H., “Gobigas project: Wood gasification to biomethane”, Chalmers University of Technology, Svebio Workshop, 24 Nov 2021

Annex: Further guidance *(delete this section in final factsheet)*

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R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	l
S	☐	H	☐	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	L

Sustainability: Relation to SDGs

	SDG				
☐	1 NO POVERTY	End poverty in all its forms everywhere	☐	10 REDUCED INEQUALITIES	Reduce inequality within and among countries
☒	2 ZERO HUNGER	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**	☐	11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable
☐	3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being for all at all ages	☒	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	**Ensure sustainable consumption and production patterns**
☐	4 QUALITY EDUCATION	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	☒	13 CLIMATE ACTION	**Take urgent action to combat climate change and its impacts**
☐	5 GENDER EQUALITY	Achieve gender equality and empower all women and girls	☐	14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
☐	6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all	☒	15 LIFE ON LAND	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**
☒	7 AFFORDABLE AND CLEAN ENERGY	**Ensure access to affordable, reliable, sustainable and modern energy for all**	☐	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
☒	8 DECENT WORK AND ECONOMIC GROWTH	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	☐	17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalize the global partnership for sustainable development
☒	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation			

***Note: Bold text means** SDG is directly related to biomass*

IEA Bioenergy
Technology Collaboration Programme

Sunpine - Esterification and distillation of tall oil

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

SunPine AB

CURRENT STATUS (2022)

Location:	Sweden, Piteå at Haraholmen industry port
Technology:	Pre-processing with esterification, distillation, purification of crude tall oil with catalyst and methanol to crude tall diesel with separation of pine pitch oil and resins, turpentine, as well as rosin acids as byproducts.
Principle feedstocks:	Crude tall oil which is a by-product in chemical pulp mills, where the technology is derived from FAME production from vegetable oils but enhanced for diesel standard quality.
Products/markets:	150,000 tonnes crude tall oil per year capacity in two process lines (100,000 and 50,000 expansion) for separation and processing to crude tall diesel and pine pitch oil.
Technology Readiness Level (TRL):	TRL 9 – actual system proven in operational environment[1]

SHORT DESCRIPTION

SunPine and Preem have developed a method to manufacture a bio-based fuel for diesel vehicles with crude tall oil as a base. The crude tall oil is a by-product from the pulp and paper industry and SunPine produces a Raw Tall oil Diesel (RTD) also named crude tall diesel, which is used for the production of Preem's tall diesel oil, which is an HVO diesel product.

The production of green diesel takes place in two stages (see Figure 1 for stage 1). The first step is carried out at the new unique facility at Haraholmen outside Piteå. Here, the crude tall oil is purified from impurities through an esterification reaction of the crude tall oil's fatty acids with methanol, followed by a vacuum distillation. Simply described, crude tall diesel and pine pitch oil are separated from the crude tall oil. Between 65 and 70 percent of the raw material becomes crude tall diesel. The crude diesel that is extracted mainly contains fatty acids but also some resin acids.

After the extraction process, the crude tall diesel is stored in a large tank at the deep harbor at Haraholmen in Piteå before it is shipped on to Preem in Gothenburg, where the product is finally refined and blended in the second stage. At Preem's refinery in Gothenburg, crude tall diesel is processed by treatment with hydrogen gas under high pressure into a high-quality diesel fuel. This takes place in a Green Hydro Treater reactor, where molecules are reformed to become identical to the molecules in fossil diesel. It provides a hydrogenated standard diesel, HVO – and not a mixture that was previously the only solution to get a greener content.

Pure sulfur is also extracted from the process, which is sold to the chemical industry. The remaining carbon compounds carbon monoxide and carbon dioxide are converted into methane gas, which is used as internal fuel.

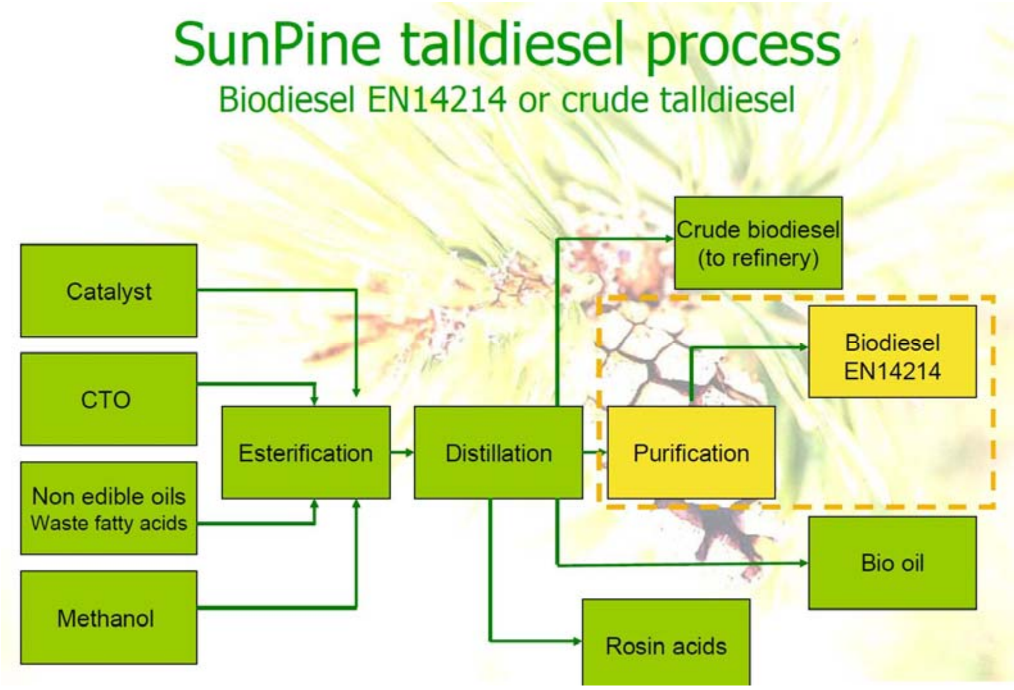

Figure 1: The SunPine process with the different steps, and has optional biodiesel production. However, the plant was built for Crude Tall Diesel for refinery upgrade to HVO diesel (© SunPine)[1]

The development started with an idea in 2005 for using the NExBTL technology then marketed by Neste for HVO production but with oils that are by-products in pulp mills. The Neste technology was patented with UOP process engineering and therefore development was made to find process ways with esterification to biodiesel. This resulted in lab testing of showing to investors and stakeholders at bench-scale a portable unit which could process crude tall oil and separate pine pitch oil and with esterification of tall oil to a clear biodiesel product.

Figure 4: Lars Stigsson, the late, visionary inventor and founder and part-owner of the SunPine plant inaugurates the plant in 2010 for biofuel production (© SunPine)[1]

Development followed for full-scale commercial plant and omitting stages of pilot plant. Construction began in 2008 and the plant capital cost was some 280 million SEK (some $28 million). The plant was inaugurated in 2010 and plant operation was started. Initial problems with salt crust formation in heat exchangers were later solved and the process was optimized into crude tall diesel production.

When production in Piteå reached full volume, Sunpine delivered 100,000 cubic meters of raw tall diesel to Preem in Gothenburg, which can then produce 500,000 cubic meters of Evolution Diesel per year with approx. 15% tall diesel content. The plant was later added with a second process line for additional 50,000 cubic meters of crude tall diesel production capacity in 2021.

What is unique about SunPine's manufacturing process is the fractionation of the crude tall oil and the post-processing into high-quality diesel. Both stages have high energy efficiency. The SunPine factory that has been built in Piteå was the first facility of its kind in the world. When the fuel product (Evolution Diesel) came out on the market with a premiere on April 9, 2011, it was a world premiere for the so-called "second generation" or advanced diesel biofuel from forest raw materials.

In retrospect, at the time of the idea in 2005 there were no facilities or plants in the whole world except for developments at Neste Oil in Finland. However, they started commercial operation in the summer of 2007 for the production of its biodiesel NExBTL. The main raw material was the same as in transesterification; vegetable and animal fats; but otherwise the NExBTL process (Neste NExt generation Biomass-To-Liquid) was much more complex and broadly resembles existing refinery processes such as hydrocracking, hydrogenation and isomerization. Thus, SunPine spearheaded new biofuel technology with then not considered raw material and developed a product which had to be further developed on how it could be processed to a final diesel product of highest value.

Latest developments in recent years have been adding several by-products like resins, and also Alpha-Pinene (α-Pinene) a monoterpene chemical which is a very valuable product, used in everything from aromas and cosmetics, to softeners and cleaning agents. Alpha-Pinene is used to produce camphor and broad-spectrum antibiotics. Studies also show that Alpha-Pinene has many positive health benefits in everything from relieving stomach ulcers to slowing cancer growth. It can even improve short-term memory.

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period	2005 - 2008	2008 - 2010	2010 – 2011	2011 - 2023
Driving frame conditions (which policy frame and/or society pushed the R&D focus)	Business development in the pulp industry and tax exemption of clean biofuels. Understanding process chemistry and materials	Business development in the pulp industry and tax exemption of clean biofuels. Understanding process chemistry and materials	Business development in the pulp industry and tax exemption of clean biofuels. Understanding process chemistry and materials	Tax exemption, reduction quota mandate.
R&D focus related to the technology itself		Verification and process parameters testing with material technology for stable operation		Plant extension
R&D focus related to accompanying topic		Plant operation with process conditions, including chemistry and process stability, dynamics and optimization		Plant extension, product expanding
Involved actors (from academia and industry) and their role			Preem (fuel upgrade) Södra (raw material) Kiram (technology licence) Sveaskog	Lawter (resins)

Public funding? If yes, mentioned the program				
Economic factors				Total investment estimated for first plant & development: EUR 30,000,00[1]
Driving factors for success			Long term operation possible overcoming typical starting problems, viable product quality for HVO processing Fuels were tested positively	
Lessons for other projects			Market players and investors covering feedstock to product with capital to achieve TRL 8.	

Information on SDGs and esp. factors with regard to economics and environment

The project contributes with the Sustainable Development Goals, seen that the residual biomass from pulp industry does not compete with food/ land use. Furthermore, it reduces the GHG emissions compared to fossil fuels.

With the collecting of wood chips from forest industry to pulp & paper manufacturing, the suppliers of are restricted to pulp mills but bring development to regional forest owners and pulp producers. The production plant also contributes locally, employing engineers, mechanics and electricians for the operation.

Because of the restricted use of feedstock flexibility the process is not readily replicable in international level, but the refinery integration is easier with decentralised production and thus scalability, depending on the availability of the residual feedstock.

Overall, the project represents a technical and commercial success. The fuels produced by the oil refinery do not require technological changes/ adaptations (e.g. in filling stations, engines and driving customs). In addition, there is possibility to produce different types of fuels depending on the process configuration, e.g. HVO gasoline, biokerosene and HVO diesel and for marine use.

The consistent capitalisation into a company with selected owners which are stakeholders and fast development into a commercial plant for revenues with the biofuels policy are explanations for the success of the project, which brought technologies up to TRL 8, developing various processes such as esterification of crude tall oil.

Figure 4: The SunPine commercial plant at Piteå (© SunPine)[1]

Info provided by: Tomas Ekbom

More information: www.sunpine.se

1. Ekbom, T., Rehnlund, B., Lindström, E. "Comparative value analysis of raw tall diesel with rape methyl ester", SunPine Report, Stockholm, 2015

Annex: Further guidance *(delete this section in final factsheet)*

A "success story" is defined as a project that is implemented, is operating at scale, contributes to the UN Sustainable Development Goals (SDGs), has wide replicability and large scale-up potential.

Replicability and/or scale-up potential

R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☐	H	☒	H	☐	h
	☐	M	☐	M	☒	m
	☐	L	☐	L	☐	l
S	☐	H	☒	H	☐	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☒	L

Sustainability: Relation to SDGs

SDG

☐	1 NO POVERTY	End poverty in all its forms everywhere	☐	10 REDUCED INEQUALITIES	Reduce inequality within and among countries
☒	2 ZERO HUNGER	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**	☐	11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable
☐	3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being for all at all ages	☒	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	**Ensure sustainable consumption and production patterns**
☐	4 QUALITY EDUCATION	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	☒	13 CLIMATE ACTION	**Take urgent action to combat climate change and its impacts**
☐	5 GENDER EQUALITY	Achieve gender equality and empower all women and girls	☐	14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
☐	6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all	☒	15 LIFE ON LAND	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**
☒	7 AFFORDABLE AND CLEAN ENERGY	**Ensure access to affordable, reliable, sustainable and modern energy for all**	☐	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
☐	8 DECENT WORK AND ECONOMIC GROWTH	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	☐	17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalize the global partnership for sustainable development
☐	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation			

***Note: Bold text means** SDG is directly related to biomass*

Enerkem - Waste gasification for alcohol production

Case studies biofuel technologies

IEA Bioenergy: Lessons learned biofuels

Enerkem Inc

CURRENT STATUS (2023)

Location:	Edmonton, Canada
Technology:	Waste gasification of SRF at elevated pressure with gas cleaning and conditioning with alcohol synthesis to methanol and ethanol.
Principle feedstocks:	Sorted feedstocks like Shredded Residue Fuels (SRF) which are sourced from municipalities and industrial wastes like plastics from dismantled vehicles.
Products/markets:	Methanol and ethanol for automotive engines being transport buses, or shipping and feedstock for chemical industry. Also, new development into DME.
Technology Readiness Level (TRL):	TRL 7 – system prototype demonstration in operational environment[1]

SHORT DESCRIPTION

Though Canada's production of biofuels using advanced technology platforms is limited, federal and provincial policy incentives favouring lower carbon intensity biofuels would provide additional support to advanced biofuels production in Canada. Canada has developed significant expertise in the development of technologies to convert non-food based feedstocks to ethanol. Examples of key players are:

- Carbon Engineering – direct air capture of CO2 with gasification to produce Fischer–Tropsch (FT) liquids
- Enerkem – gasification (municipal residues) and catalysis
- Ensyn – pyrolysis-based technology for renewable heating fuel and refining coprocessing to transport fuels
- Greenfield Global – integration of grain-based and cellulosic-based ethanol production
- Iogen – enzymatic hydrolysis (agricultural residues) and biogas-based fuels

The Canada-headed thermochemical process developer Enerkem is a private company founded in 2000 with some +200 employees. They have proprietary clean technology developed in-house and a first full-scale commercial biorefinery in Edmonton apart from pilot and demonstration facilities in Québec. Enerkem is developing similar facilities in North America and Europe. Enerkem makes cellulosic methanol and ethanol (which can be used as fuel or other industrial chemicals) from syngas by recycling carbon in non-recyclable municipal solid waste (MSW).

In 2014, Enerkem launched the world's first full-scale MSW-to-biofuels and chemicals facility in Edmonton, Alberta. Enerkem's Edmonton plant started producing only methanol, but with the addition of a methanol-to-ethanol converter unit, the plant also began producing ethanol in 2017, with a current annual methanol-ethanol production capacity of 38 million liters. The process layout is given in Figure 1 with its process steps.

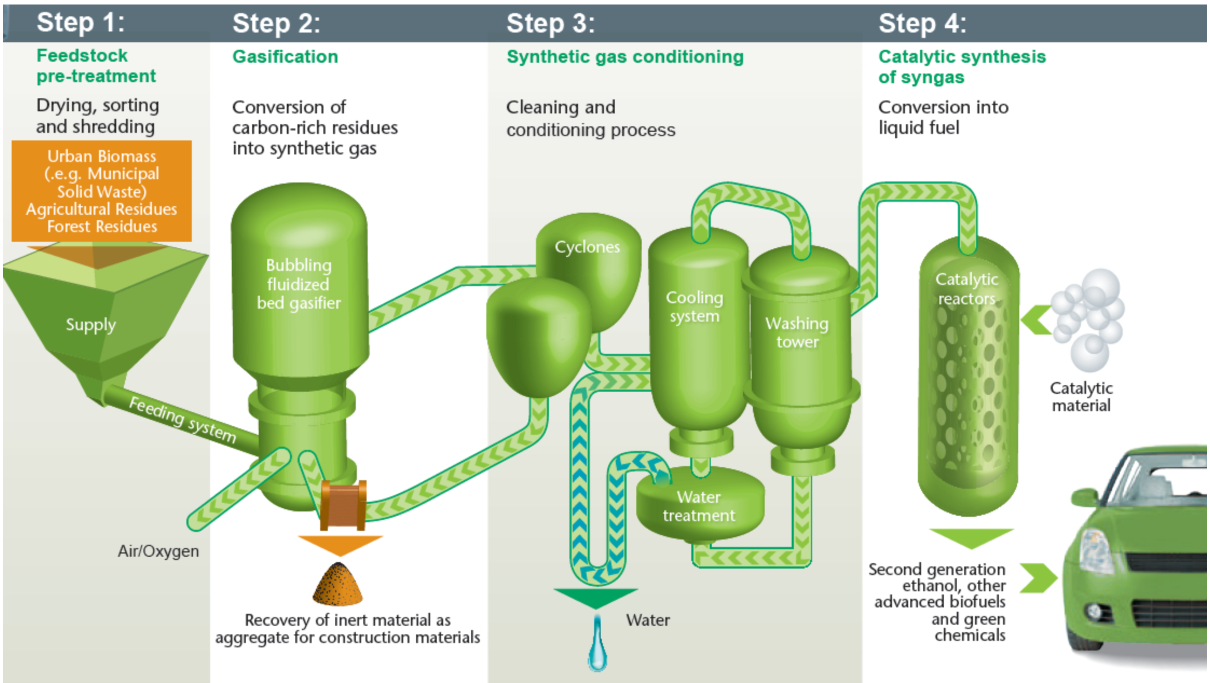

Figure 1: The Enerkem process with the different process steps, and has optional alcohol production depending on market, methanol or ethanol. (© Enerkem)[1]

The Edmonton plant became the first ever MSW-to-cellulosic ethanol plant certified to meet renewable fuel obligations under the U.S. Renewable Protection Standard (RFS) and to generate Renewable Identification Number (RIN), having received U.S. Environmental Protection Agency (EPA) pathway approval in 2017. The plant can use a variety of fuels ranging municipal solid waste and waste plastics and biomass residues but mostly focuses on SRF which lends it thanks to properties for the developed gasification process.

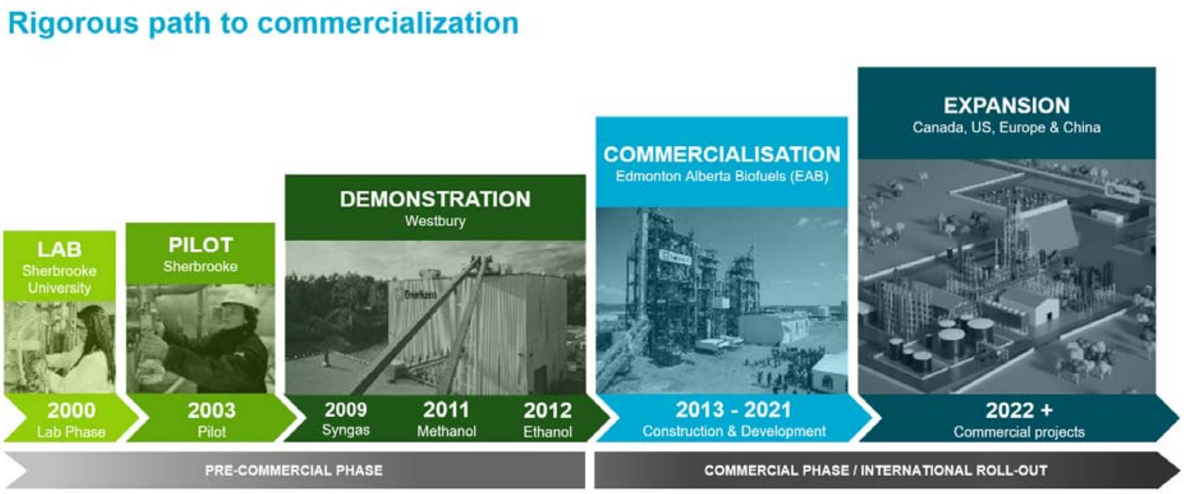

Figure 2: The Enerkem development has been long and rigorous with unique proprietary processes along the process chain, instead of purchasing or licensing certain process steps. (© Enerkem)[1]

The Enerkem technology development encompasses from lab-scale research to commercial-scale project development and the broader benefits of 'recycling' carbon in waste into advanced, renewable transportation biofuels and as a low-carbon and circular chemical intermediate. The time-line is shown in Figure 2.

The largest milestone for the company was achieved in June 2014 when did Enerkem opened its first commercial-scale facility in Edmonton, Alberta to convert municipal solid waste (MSW) to biofuels and biochemicals. Since then the plant has achieved all its operational milestones including ISCC certification and methanol to ethanol stage. However, details have not been given concerning the commercial plant in Edmonton on continuous operation as a fully-commercial operating plant. There are still operational availability, yields and process chemistry learnings, which have been for some time. There is also missing plant data on net efficiency, however, this may more be of importance for positive costs of the feedstocks rather than negative costs.

In parallel and since, the company has engaged in a waste-to-chemical project in Europe and, perhaps more significantly, has initiated a rollout joint-venture in China. The development plans for other plants have centered on Enerkem's first European project which is in Rotterdam apart to the Varennes Carbon Recycling project in Quebec, Canada. The Rotterdam plant will produce up to 220,000 tons of advanced (bio-)methanol from a mixture of up to 360,000 tons of non-recyclable commercial & industrial wastes including mixed waste plastics.

The case study shows to demonstrate how innovative technologies such as Enerkem's, is producing both a sustainable, 'circular methanol' for use as a key commodity feedstock by the chemicals industry and an advanced bio-methanol for use in a range of fuel applications using non-recyclable wastes. It will highlight the benefits to doing so for both downstream markets and highlight the importance of developing highly integrated plants as part of sustainable chemical and biofuels clusters.

Federal and provincial-level renewable fuels programs have continued to support conventional biofuels production and use across Canada. From 2006 through 2010, the provinces of British Columbia, Alberta, Saskatchewan, Manitoba and Ontario established a blending requirement of 5 to 8.5% for ethanol in gasoline and 2 to 4% for renewable content in diesel. Federal use mandates followed thereafter, and, since December 2010, federal regulations have required fuel producers and importers to have an average ethanol content of at least 5% based on the volume of gasoline produced or imported.

Since July 2011, federal regulations have required fuel producers and importers to have at least 2%, on average, renewable content based on the volume of diesel fuel and heating distillate oil that they produce or import. The current federal Renewable Fuels Regulations include a trading system and administrative, compliance, and enforcement provisions such as recordkeeping and reporting.

In December 2017, the federal government released its Regulatory Framework on the Clean Fuel Standard (CFS), which describes how Canada will transition from volumetric-based requirements towards a carbon intensity-based approach. Volumetric requirements under the current Renewable Fuels Regulations will remain in force until Environment and Climate Change Canada (ECCC) clarifies how Canada will transition to carbon intensity benchmarks. ECCC is the department within the Canadian government responsible for coordinating environmental policies and programs as well as for preserving and enhancing the natural environment and renewable resources.

Canada is one of the highest ranked countries amongst the Organisation for Economic Co-operation and Development (OECD) for public expenditures on energy RD&D as a percentage of Gross Domestic Production (GDP). Expenditures are channeled by the federal government, provincial governments and industry on renewable and clean energy research, development and demonstration (RD&D). Bioenergy related research is being conducted across Canada in universities and colleges, federal and provincial laboratories, and industry. RD&D has been supported at both the federal and provincial/territorial levels.

There are various types of government support provided in Canada for biofuels, spanning across all stages of the biorefining process. The most important types of support available include: Grants and low-interest loans in RD&D and business planning and, plant construction. In addition, for production there are fuel tax exemptions, producer payments and price support with mandated biofuel blending requirements and tariffs. Then, in consumption tax-breaks for the purchase of biofuel-consuming vehicles. There are variety of investment subsidies that support or have supported the production and consumption of bioenergy and biofuels.

IMPORTANT STEPS ALONG THE INNOVATION CHAIN TO CURRENT STATUS

Criteria	Basic research (TRL 1-2)	Applied research (TRL 2-5)	Technical development (TRL 5-8)	Market incorporation (TRL 8-9)
Time period	2000 - 2008	2009 - 2012	2013 – 2021	
Driving frame conditions (which policy frame and/or society pushed the R&D focus)	Business development in the pulp industry and tax exemption of clean biofuels. Understanding process chemistry and materials	Development of process reactors and engineering. Understanding process chemistry and materials	Agreement of feedstock for supply contract and biofuels policy	
R&D focus related to the technology itself		Verification and process parameters testing with material technology for stable operation	Large-scale development with operation and integration of selected processes. Understanding process chemistry and materials	
R&D focus related to accompanying topic		Plant operation with process conditions, including chemistry and process stability, dynamics and optimization		
Involved actors (from academia and industry) and their role	Sherbrooke University			

Public funding? If yes, mentioned the program				
Economic factors			Total investment estimated: Edmonton plant as $75 million capital project[1]	
Driving factors for success			Long term operation possible overcoming typical starting problems, viable product quality for HVO processing	
Lessons for other projects			Market players and investors covering feedstock to product with capital to achieve TRL 8.	

Information on SDGs and esp. factors with regard to economics and environment

The project contributes with the Sustainable Development Goals, seen that the decentralized conversion of residual biomass (e.g. from agriculture or forestry) does not compete with food/ land use. Furthermore, it reduces the GHG emissions compared to fossil fuels.

With the waste and biomass collection, the suppliers of feedstock can add value to its residual biomass and densify its energetic value, which brings development to regional producers. The production plant also contributes locally, employing engineers, mechanics and electricians for the operation.

Due to the feedstock flexibility and usage of lignocellulosic residues, there is no requirement of structure changes, therefore the process is replicable in international level, depending on the availability of the residual feedstock.

Overall, the project represents a technical success but not commercial as the first plant is still not fully operational after many years. The fuels produced do not require technological changes/ adaptations (e.g. in filling stations, engines and driving customs) and is flexible to produce different types of fuels depending on the process configuration.

The consistent research and own funding with step-wise development and steady continuation with negative feedstock costs are explanations for the success of the project, which brought technologies up to TRL 7.

Figure 4: The Enerkem commercial plant in Edmonton (© Enerkem)

Info provided by: Tomas Ekbom

More information: www.enerkem.com

1. Miles, Alex "Waste as a valuable resource for making high-grade biofuels", Advanced Biofuels Conference, Gothenburg 2018

Annex: Further guidance *(delete this section in final factsheet)*

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Replicability and/or scale-up potential

R = Replicability
S = Scale-up

H = high
M = medium
L = low

	Local/regional		National		International	
R	☒	H	☒	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	l
S	☒	H	☒	H	☒	h
	☐	M	☐	M	☐	m
	☐	L	☐	L	☐	L

Sustainability: Relation to SDGs

SDG

☐ 1 No poverty — End poverty in all its forms everywhere

☒ 2 Zero hunger — **End hunger, achieve food security and improved nutrition and promote sustainable agriculture**

☐ 3 Good health and well-being — Ensure healthy lives and promote well-being for all at all ages

☐ 4 Quality education — Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

☐ 5 Gender equality — Achieve gender equality and empower all women and girls

☐ 6 Clean water and sanitation — Ensure availability and sustainable management of water and sanitation for all

☒ 7 Affordable and clean energy — **Ensure access to affordable, reliable, sustainable and modern energy for all**

☐ 8 Decent work and economic growth — Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

☐ 9 Industry, innovation and infrastructure — Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

☐ 10 Reduced inequalities — Reduce inequality within and among countries

☐ 11 Sustainable cities and communities — Make cities and human settlements inclusive, safe, resilient and sustainable

☒ 12 Responsible consumption and production — **Ensure sustainable consumption and production patterns**

☒ 13 Climate action — **Take urgent action to combat climate change and its impacts**

☐ 14 Life below water — Conserve and sustainably use the oceans, seas and marine resources for sustainable development

☒ 15 Life on land — **Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**

☐ 16 Peace, justice and strong institutions — Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

☐ 17 Partnerships for the goals — Strengthen the means of implementation and revitalize the global partnership for sustainable development

***Note: Bold text means** SDG is directly related to biomass*

IEA Bioenergy

Technology Collaboration Programme