Assessment of successes and lessons learned for biofuels deployment

Report Work package 5 |
Synopsis / synthesis of key issues

IEA Bioenergy TCP
Intertask project of Task 39, Task 40 and Task 45

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1. Introduction

There are major challenges associated with achieving a climate neutral society by 2050 and fulfilling sustainable development goals (SDGs), as expressed in IEA's Net Zero by 2050 roadmap[1]. Among societal sectors, transport is proving to be an extremely difficult sector to decarbonize – which also implies the switch from fossil carbon to renewable carbon based fuels. IEA analysis shows that the rate of progress in renewable fuels is well below what is needed to sufficiently contribute to these targets.

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 decarbonisation targets. 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 climate neutrality goals. 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.

Therefore, this intertask project "Lessons learned biofuels" seeked 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 the needed clean energy transition.

This project examined the technical, economic, societal and political reasons underlying the past and ongoing booms and busts cycles of biofuel technologies development, demonstration, deployment and replication. The aim was to identify key factors for technology successes and the best policy framework conditions as well as the measures for stimulating increased future markets for production and consumption of sustainable transport biofuels.

The work was carried out from 2020 to 2023 in a collaboration between three IEA Bioenergy Tasks (Task 39 "Biofuels", Task 40 "Deployment" and Task 45 "Sustainability"). The work was organized in five work packages and one work package dedicated to project management. The structure for the project is shown in Figure 1, in which the division of the work packages and the leadership is presented. In addition, workshops were held on a number of topics.

[1] Available at https://www.iea.org/reports/net-zero-by-2050

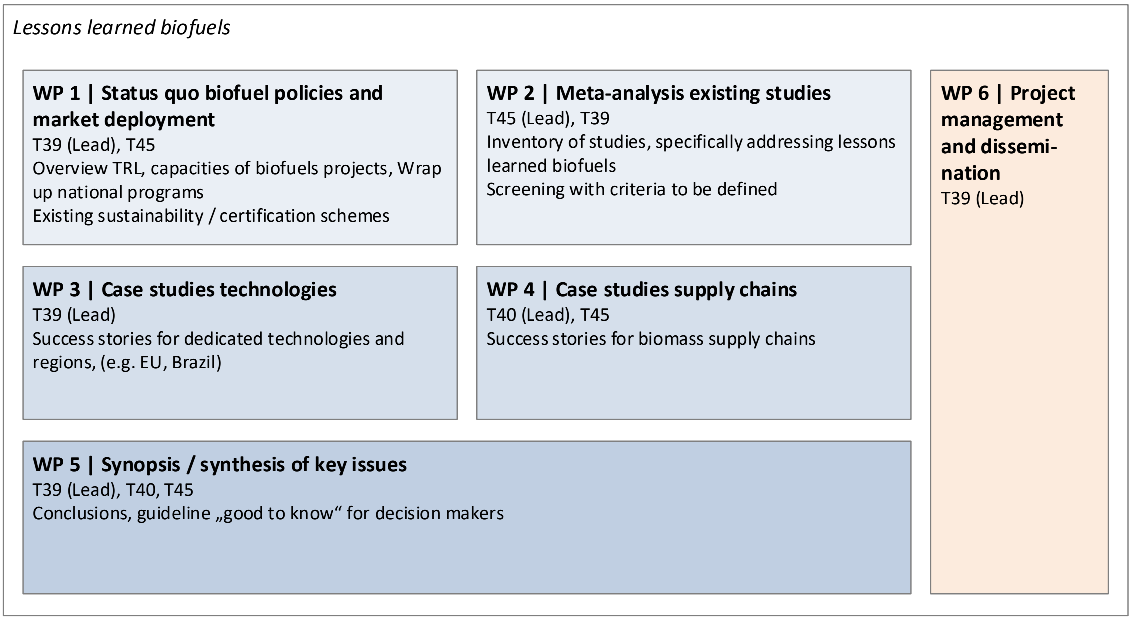

Figure 1 Project structure

2. Methodical approach

Providing a synopsis of this project, work package 5 is dedicated to draw conclusions about "successes and lessons learned on biofuels deployment" and developing a "guideline/good to know" brief for decision makers.

For this the results of the work packages 1 to 4 (cf. Figure 1) were used. In addition to that, a workshop was organized at early stage of the project to present the preliminary results of the project, gather expertise from industry and academia partners and discuss the topics addressed in the "Lessons learned". The workshop with the title "Guidelines to overcome barriers for commercialization of advanced biofuels" was organized by SVEBIO and realized in a hybrid format in November 2021. Moreover, SVEBIO was organizing and involved in two other workshops in April 2021 and March 2022 that provided input for this project as well. The results of these workshops are summarised in a separate report.

Based on the work package specific reports[2] as well as expert inputs from workshops, this synopsis report allows to answer both research questions of this lessons learned biofuels project:

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

[2] Available at https://www.ieabioenergy.com/blog/task/lessons-learned-biofuels/

3. Results and discussion

As follows a synopsis of the key results from the work packages 1 to 4 is given; in addition the main results of the workshops held in 2021 and 2022 are also summarized. Moreover, notes for a guideline for stimulating biofuels development are presented.

SYNOPSIS OF KEY RESULTS FROM THE WORK PACKAGES

Status quo biofuel policies and market deployment

This work package essentially coincides in scope with the Task 39 Implementation agenda [IEA Bioenergy-T39 2022]. The assessment carried out highlighted the most important factors that have been incorporated and also identified the balance between market-related versus technology-related policy instruments that have proven to be most effective.

Despite the relatively minor share of renewables in transport (globally about 3%), biofuels continue to be a central fuel option in most strategies to decarbonise transport. Regardless of an ongoing trend towards greater electrification of road transport, biofuels still account for more than 90% of renewable energy in the transport sector and remain central to many national and sub-national renewable transport policy frameworks.

Biofuels production continues to increase globally at an average annual rate of 4% over the past 10 years. An overview on renewable fuels today as well as required amounts until 2050 is shown in Figure 2. Conventional bioethanol and biodiesel (FAME) are currently the renewable fuels with the highest production amounts worldwide followed by a rapidly growing market for HVO/HEFA and to a minor share biomethane/biogas. The total production of about 4 EJ, together with fuel capacities planned and under construction of about 2 EJ, needs to be multiplied by a factor of 5 to 10 to meet the required demand of renewable fuels (biofuels and e-fuels) worldwide by 2050.

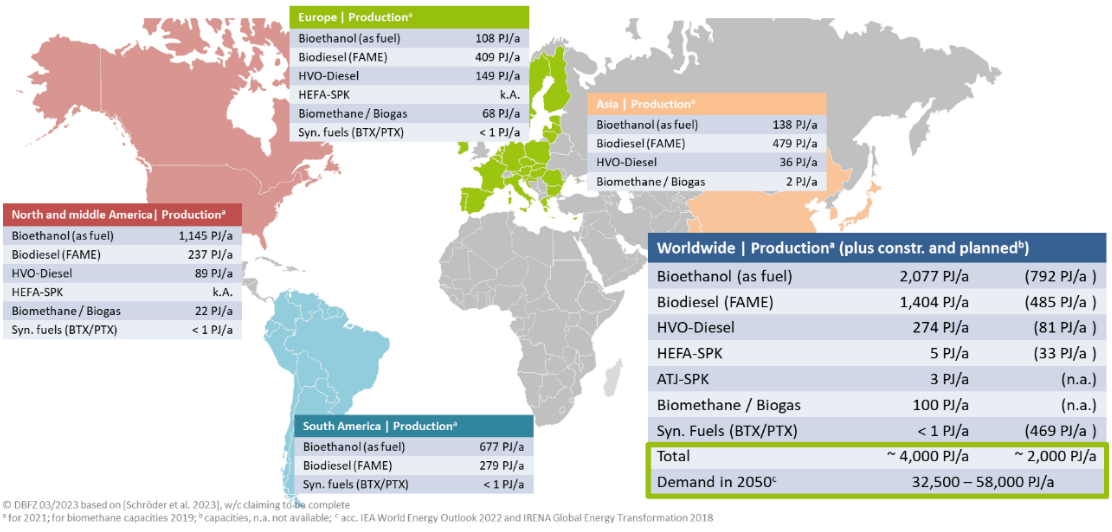

Figure 2 Overview on production of renewable fuels (biomass based and e-fuels)

National experiences show that biofuel policies have been and still are essential for the past and future development of the biofuel market. Technology-push policies (e.g. CAPEX/OPEX for technology development) are focussing on research, development and demonstration (R&D&D) while market-pull policies (e.g. blending mandates, quotas, multi-counting mechanisms) allow creating a certain demand of fuels for relatively mature technologies. Sustainability requirements are being increasingly incorporated into policies.

Biofuel mandates alone (without additional minimum GHG reduction requirements to be acceptable) usually are not sufficient enough to support actors reducing the carbon intensity along the biofuel value chain. Reducing the carbon intensity of biofuels brought to market is incentivised by so-called ‘low carbon fuel standards’ (like in parts of the US and Canada as well as in Brazil) or GHG emission quotas (like in Sweden and Germany) respectively.

Technology-push policies have successfully encouraged R&D&D, particularly for advanced biofuels. This is true especially in countries where biofuel markets are established (e.g. US, Canada, Brazil, EU). However, despite considerable progress being made in the technical aspects of advanced biofuels production, stable, supporting policies are required to establish commercialization.

Countries that are using both policy instruments (technology-push and market-pull) have achieved most success in growing markets for biofuels production and use.

To enhance the effectiveness of policies in creating a target oriented stable environment for increasing shares on biofuels several uncertainties need to solved. A primary factor is long-term certain biofuel policies that allow investments and mitigate the risks especially for advanced biofuels. Other factors to be addressed are: non-compliance costs, competitive resource and product markets, future funding and incentive programs, unforeseen impacts to global trade (pandemics, wars, crisis, taxes). Moreover, the lack of commitment to stop investments in fossil-based industries hinders market growth of renewables.

Policies promoting renewables in transport have so far been focusing primarily on road transport, which accounts for the vast majority of the total energy use. Despite being large energy consumers and carbon emitters aviation and shipping received less attention. However, this is changing and policies are clearly starting to address these transport sectors.

Meta-analysis on existing studies

This work package made a meta-analysis on several studies dealing with “successes and lessons learned for biofuels deployment” for advanced as well as from conventional biofuels. The focus was mainly on biofuels with high TRL, especially ethanol and biodiesel, which are already widely used in many countries and therefore are mature in the market.

Six parameters were defined to analyse and discuss different available biofuels (ethanol, biodiesel/FAME, HVO, BTL/DME and SNG) in different regions (Brazil, US, Europe). The parameters feedstocks, by-products, public policies, implementation/ replication potential, environmental aspects and contribution to SDGs were analysed in a semi-quantitative method.

Among the analysis of existing studies, different points were discussed about the implementation of biofuels worldwide. Firstly, the two biggest producers and consumers of bioethanol, Brazil and USA, have a long history of improvement in the biomass conversion technology. Factors that directly impact the biofuel viability and ecological impact such as crop yields and greenhouse gas emissions over the biofuel production value chain gradually improved in the last years. The same development could be verified in Germany, which had in 2011 a mean value of emissions savings of 41% of the biofuels utilized in the country; in 2019, the emissions savings mean value increased to 81%. Biofuel blending mandates and proper public policies were important to support implementation and technological improvements.

Also, the ongoing economic crisis related to the covid pandemic and the Ukrainian war affected the biofuels industry in many countries, and it will take some time for the biofuel production and use to recover to pre-crisis levels.

Published indicators for 2G/advanced ethanol are seldom available, but evidence exists that technological bottlenecks are being overcome. BtL, Bio-SNG, HVO, and straw-derived 2G ethanol show suitable indicators of environmental impact, SDG, and feedstock diversity to be replicated in different regions but economics is still a challenge.

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. Earlier innovations such as Biomass-to-liquid (including biojet), Biomethane, HVO, and straw-derived ethanol show suitable indicators of environmental impact, sustainable development, and feedstock diversity to be replicated in different regions. However, published indicators are seldom available which indicates that technological challenges and cost limitations are still to be overcome to reach market maturity.

Most biofuels in the market today are conventional biofuels such as ethanol (from sugar cane or corn) and biodiesel (from soybean oil or palm oil). These biofuels have predominantly crops, often food or feed crops, as their main feedstock. This to some extent also applies to HVO (although these are more and more produced from waste oils). Despite these biofuels being success stories, according to metrics of some regions in the world, the production or consumption from food/feed crops should decrease or be discontinued in the future. Yet, at this point, other biofuels produced exclusively from crop residues and non-food crops seem not to be economically produced on a scale large enough to replace the current volume of conventional biofuels.

In view of the need to sharply increase biofuel production to abate the climate crisis, restrictions on some biofuel feedstocks may have to be rethought, especially where they can be sustainably produced, until more and more types of non-food biofuels become market mature.

Case studies technologies

In this work packages case studies from corporate technologies under development were elaborated to illustrate examples of successful progress in developing and scaling up advanced/emerging biofuels production technologies. Specific case studies from Germany, Sweden and Canada were investigated (Table 1). Some can be considered technical successes but have yet to reach commercial deployment; others have started commercial roll-out in the market. Apart from identifying success factors, lessons learned in shortcomings or other issues in the commercial development are also given in the case studies.

Table 1 Overview of studied case studies

Stakeholder	Feedstock	Process characteristics	(Intermediate), Final product, (byproducts)	TRL
Clariant (Germany)	Cellulose (e.g. straw)	Steam explosion, enzymatic hydrolysis, fermentation, purification	(Sugars), Ethanol, (lignin, vinasse)	8
KIT (Germany)	Cellulose (e.g. wheat straw)	Fast pyrolysis, gasification, gas cleaning, Methanol/DME/Bio-gasoline synthesis	(Syngas, biosyncrude), Methanol/DME/Bio-gasoline,	6-7
CHOREN (Germany)	Cellulose (Wood chips from recycled wood and residual forestry wood)	Two stage gasification, syngas cleaning/ conditioning, Fischer-Tropsch synthesis	Syngas, diesel fuel	6-7
Chemrec (Sweden)	Black liquor from pulp and paper	Gasification, syngas contionierung, methanol/DME synthesis	Methanol, DME	7
GoBiGas (Sweden)	Cellulose - Wood pellets and (dry) wood chips	Gasification, syngas cleaning, methanation (synthesis)	(Syngas), Methane	7-8
Sunpine (Sweden)	Cellulose - Spruce and pine wood	Esterification, distillation, purification of crude tall oil with catalyst and methanol	(crude tall diesel), diesel fuel, (pine pitch oil, resins, turpentine, rosin acids)	9 (11)
Enerkem (Canada)	Refuse derived fuel and plastic	Gasification and gas cleaning, alcohol synthesis	Alcohols	7

Clariant - Sunliquid® Enzymatic hydrolysis to ethanol. This technology was developed from about 2006 and the first commercial facility recently brought to operation in 2022 in Romania. The technology development was supported by the operation of a pilot/demonstration plant and experience gaining through funding for the construction of the first commercial facility.

KIT - Bioliq® pyrolysis and gasification with synthesis. The KIT Bioliq technology platform is engaged in the gasification technology scale-up, but also incorporates other key processes for the production of biofuels as pyrolysis, methanol/ DME synthesis and methanol-to-gasoline synthesis. The production facility fulfils its objective of a research platform and is actually being used in different projects.

CHOREN – Gasification and Fischer-Tropsch synthesis. Having a pilot plant in operation since 1997, Choren built a demonstration plant in 2009 and had plans to build a commercial plant in 2012, but the company declared insolvency in 2011 and the production of biofuels through Fischer-Tropsch synthesis could not be further scaled-up. Until now there is no success in reactivation of this technology approach.

Chemrec – Black liquor gasification and methanol/DME synthesis. Chemrec has demonstrated the world's only plant for bio-DME production by gasification of black liquor including an extensive technology verification with many thousend hours of operation. A planned commercial large-scale project still hasn't reached a go-ahead. Overall, the project represents a technical success. The fuels produced were also tested in new DME trucks.

GoBiGas - Biomass gasification with methanation. GoBiGas is part of Göteborg Energi's (Gothenburg Energy) investment in reducing the use of fossil fuels. The purpose of the project was to demonstrate the possibilities of gasification technology and to build a plant for a biomethane product of natural gas quality. Despite technological success a commercial plant was not realised due to missing economic competitiveness.

SunPine – Esterification and distillation of tall oil. 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 also named crude tall diesel, which is used for the production of Preem's tall diesel oil, which is an HVO diesel. The process is commercial and currently supplies around half of the biodiesel product sold by Preem.

Enerkem – Waste gasification for alcohol production. In 2014, Enerkem launched the world's first full-scale MSW-to-biofuels and chemicals facility in Edmonton, Alberta, and started producing methanol. With the addition of a methanol-to-ethanol converter unit, the plant also began producing ethanol in 2017. All its operational milestones including ISCC certification were achieved.

The essential learnings from these case studies are related to:

- Financing new production plants: this includes secured biomass supply/local feedstock availability with feasible feedstock prices, stability of the regulatory framework, longer perspective, binding mandates, the CAPEX dimension and financing costs. Financing of first of a kind technology plants requires higher support (e.g. guaranteed biofuels price) than following plants.
- Political decisions: these ultimately and irrevocably determine success of biofuel production projects.
- Technology improvement: large first-of-its-kind plants require special regulation that can gradually be shifted from specific to general with increasing maturity and number of plants. Biofuels quotas alone are not sufficient to support new technology and large kind plants; additional support and security on value of renewables is needed.
- Awareness of infrastructure requirements: especially cost reasons and compatibility with the existing infrastructure for plan operation and handling of feedstocks and plant products are key issues.

Case studies supply chains

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.

This work package evaluated case studies for feedstock supply chains from multiple viewpoints, highlighting lessons from biorefineries and pulp mills using short rotation wood fibre crops (Brazil), European experiences in development of bio-based supply chains for torrefied woody biomass, pioneer biorefineries in the US (traditional feedstock pre-processing for herbaceous feedstocks) and conceptual depots producing conversion-ready feedstock and co-products. The focus was on biomass feedstock supply chains which includes all logistic operations to move biomass from the supply origin, for example field or forest, up to the 'throat' of the biorefinery.

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.

Since there is a time lag between the harvest and use of biomaterials, issues related to degradation, feedstock losses, and inconsistencies in quality emerge, which in turn adversely impact yield and throughput at the biorefinery. Approaches including in-field preprocessing, alternate storage designs, and utilization of feedstock blending can help overcome some of the challenges faced by pioneer biorefineries.

Consistency of feedstock quality is an important consideration for the development of reliable feedstock preprocessing systems. From the experience of pioneering biorefineries on herbaceous feedstocks, problems such as high ash content of feedstock, impurities and contaminants, wide particle size distribution and inconsistent feedstock quality were identified. As a result, the biorefineries experienced problem in processing these feedstocks, including instances of clogging in equipment and abrasion of equipment due to high levels of abrasive content in feedstock. Some of these problems can be tackled through the torrefaction of the biomass.

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. However, experience and feedback from manufacturing companies to date show that wherever torrefied biomass is used in production processes other than purely as an energy source, there is much less flexibility with regard to the composition of the feedstock, i.e. the torrefied biomass, than there is in the combustion processes in power plants, which can be adapted within limits

The processing of raw feedstock into water-resistant solid or liquid bioenergy carriers naturally also has a significant influence on the design of the transport chains. Enabling the use of existing infrastructure, such as the coal chain, reduces investment need, increases transport efficiency and further reduces specific costs. And even if the willingness to invest in infrastructure increases with the importance of biofuels in international trade, it is probably much cheaper overall to trim biofuels so that existing infrastructure can be used instead of replacing it at high cost.

In addition, if biomass is shipped in large units along the main shipping routes the specific costs (energy based) are moderate. But once off these main routes and especially when only smaller quantities are transported the share of transport costs in full costs of product is very significant. This situation disadvantages resources in remote areas and even cuts off some of the possibly valuable resources from biofuel markets.

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.

Development of sustainability certification schemes and their benchmarking are important and necessitating transparency and verification of the auditing process from qualified professionals to ensure quality and robustness of a certification scheme are vital.

The carbon intensity of fuels, including biofuels, is becoming an increasingly relevant metric in GHG mitigation policies of the transportation sector. Supply chain GHG emission calculations at the commodity level can be used to demonstrate compliance with sustainability criteria or compare the GHG performance of different pathways. other sustainability impacts and important trade-offs, for example, between climate and other impacts such as water use, biodiversity and socio-economic impacts are also essential to consider. Important lessons learned from the challenges and controversies from conventional biofuels (for example ILUC), and electricity and heat (for example biogenic carbon issues), assessment tools, and efforts to safeguard sustainable production are therefore relevant to facilitate the sustainable deployment of advanced biofuels.

WORKSHOP SUMMARIES

A comprehensive summary of the workshops undertaken in 2021 and 2022 in the frame of this intertask project is given in a separate report, which is available at the project website[3]. Below the main results of the workshops are summarised. They have to be reflected as topics of discussion at the respective time when the workshops took place.

Workshop on new investments and risks in April 2021

This Swedish workshop dealt with the central question: “which are the factors that you consider to play an important role in the investment process for biorefineries?” and on how to manage risks. In a stepwise approach the group concluded with the following factors on:

- **Financial aspects** including management experiences, projects’ calculated profitability, first-of-its-kind funding and form of financing
- **Political aspects** including long-termism, strength and credibility of the energy legislation, share of the reduction obligation from non-food raw materials, energy and CO_2 tax as well as other control instruments like feed-in tariff, bonus/malus, guaranteed minimum price level and state aid rules
- **Market aspects** including offtake agreement, GHG performance, price and volume as well as access to raw materials in the context of the energy situation/quality, price and volume

[3] Available here https://www.ieabioenergy.com/blog/task/lessons-learned-biofuels/

- **Technology aspects** including technology maturity, refinery technology TRL scale and the potential of the product for increased added value.

Workshop on guidelines in November 2021

The workshop discussed aspects to overcome the technical, economic, societal and political barriers in past and ongoing booms and busts cycles of biofuel technologies and to stimulate increased future markets for production and consumption of transport biofuels. The key queries were addressed through diverse presentations, panel discussions and breakout sessions that could offer insights for the project. In addition, in relation to overcome barriers it was also discussed how to increase investments in new biofuels production plants.

First of its kind projects – how to get to market. Experiences of demo projects like BioDME/Chemrec and Gobigas (cf. also work package 3) showed that although the technical feasibility of the demonstration facilities was confirmed and there were ongoing projects for the further scale-up of the technologies, no decisions have been taken for further commercial scale investments as commercial break-evens have not been reached decisions. It was expected that the production costs could be reduced after a successful operation of a first-of-a-kind plant, but there was no clarity on long term regulations that could support such a long-term investment.

Learnings in biofuel developments. In 2020, the majority of biofuels utilized in Europe still came from crop-based biofuels and the biggest part of new car registrations came were petrol (47.5%) and diesel (28%) vehicles. In Europe, the majority of gasoline that time was sold as E5 (84.2%), the remaining market share divided in E0 (4.2%), E10 (11.5%) and E+(Mixture above E10, 0.2%). The European bioethanol certifications shows that the GHG emissions savings increased from 50.7% in 2010 to 75.5% in 2020 compared to fossil values. The company Raizen brought the perspective of bioethanol from the view of the biggest bioethanol supplier in Brazil. The possibility of producing advanced biofuels is accessed mainly from the by-products of the already established sugarcane industries. Owning an operational facility of biogas from vinasse and advanced bioethanol from bagasse, the company is already building further facilities, having therefore succeeded in overcoming difficulties from first-of-its-kind plants. The strategy of the company is to expand further the product portfolio with advanced fuels as ethanol, biomethane and sustainable aviation fuels.

Advanced biofuel projects – accelerating development to large scale. The insertion of a first-of-a-kind plant in the market can bring diverse risks, from technology, product quality, feedstock availability to financing. Thus, a complete study of all these factors has to be realized, having a clear analysis of the risk management process. Technologies for production of advanced biofuels as HVO and co-processing could be able to supply a large fuel demand, as they are easier to be implemented. Technologies as Fischer-Tropsch and advanced bioethanol are still limited due to lack of non-food biomass value chains.

A summary of the different breakout session is presented below.

Boom and bust of (Swedish) biofuels projects. The markets for biofuels are largely influenced by political decisions. The political driving forces have been several, for example to reduce the dependency on oil imports, create new jobs and reduce CO_2 emissions from the transport sector. As biofuel markets are international, strategy changes in individual countries or regions also affect the national market. The participants regarded the European Fit for 55 proposals overall positive with comments e.g. on the renewable energy share by 2030 and a more positive view of bioenergy, on the emission trading system including CO_2 prices that support to shift from fossils to renewables, on the energy tax system based on energy content which is seen as fair approach, on international CO_2 pricing for a global impact as well as a separate quota for aviation fuels.

Biofuels in aviation and marine - successes and learnings. At the time of the workshop there were good opportunities to coordinate and increase quotas for biofuel aviation. Norway had already decided on a quota and Sweden and the EU had the proposals for ReFuelEU aviation and FuelEU Maritime[4]. This could go beyond the voluntary commitments that currently exist in some countries and among airlines. This can provide impetus for commercial facilities. In the same way as for aviation, shipping can and will change, initially with a directive in the EU on the reduction of emissions. However, it must be supplemented with more control instruments to really give impetus to a changeover and that advanced biofuels can become successful investments in the long term.

Carbon tax / pricing - lessons and successes for biofuels. The lesson learned is the need for regulators to focus on how to handle price and volatility risks, which are the most challenging risks to handle in renewable fuels production and the need to provide grandfathering for projects as subsequent projects move down in cost on the learning. A large portion of the value of renewable fuels is politically created and is therefore extremely sensitive to changes or uncertainty in policy. A discussed approach for investments in advanced biofuel projects is the concept of 'contract for difference' (CFD) which is typically a civil law contract between two parties under which one or both parties commit to pay the other party the difference between a set price (strike price) and a market price or value.

Technical and economic analysis of biofuels. Questions were discussed on e.g. driving factors for technology success, R&D focus/challenges to overcome related to the technology itself, time period for scale-up, involved actors and their role as well as public funding. Key messages were:

- Start with fuels that have a high TRL like HVO/HEFA (or biomethane) and also use the potential of co-processing to reduce overall GHG emissions. These options are also associated with the lower investment risks within the advanced biofuels options. Establish proper value chains and improve them.
- Use all options in a broader context of biobased economy incl. biomass/energy crops as carbon source.
- Moreover, start doing and establishing a transparent monitoring system to continuously check regulative frame, standards and norms and adapt them if necessary.
- Infrastructures should be developed in a transnational way (not each country is able to build up infrastructures for many different options).
- Last but not least, strengthen the awareness of risk, consolidated total cost of ownership

[4] Which are approved in 2023.

and challenges of investments and plant operation along the value chain.

The place of biofuels in an electric vehicle world. The means for biofuels to co-exist with electric vehicles was discussed. Biofuels are often overlooked in public discussions on how to decrease emissions of the transport sector. Electricity is considered as replacement of renewable fuels instead of a complement. The extent to which biofuels and battery electric vehicles are sustainable is debated, and differ across markets due to different biofuel production and electricity generation methods. Current policy changes are not necessarily turning to renewable fuels. The EU and USA have stringent policies for tail-pipe emissions in vehicles (instead of life cycle emissions), which in future will be hard to meet with combustion engines. Proven benefits of biofuels are less acknowledged (reduction of GHG emissions when replacing fossil fuels, well established industry in place, job generation, benefits for air quality etc). While the potential negative aspects of biofuel production on food production, availability and pricing have received more attention, there are also positive indirect effects from increased biofuel production on food production, by e.g. helping to improve rural infrastructure and rural development. In addition, the opportunities of electro-fuels have been discussed and the need of hydrogen and CO_2 (e.g. from flue gases, side streams of liquid biofuels, upgrading of biogas or captured from the air) for their production.

Workshop on industrial use of biofuels in March 2022

The purpose of the workshop was to highlight experiences of major industrial projects in Sweden and to identify opportunities for continued R&D and interaction to facilitate the necessary transition and finally to initiate Swedish networking in the area, both nationally and internationally.

The need for knowledge about experiences of how obstacles can be solved is crucial for a rapid changeover to be achieved. This applies to experiences from the entire chain of planning, implementation and operational stages.

There are significant changes in the industry underway, including but certainly not limited to electrification, development of (sustainable or not) hydrogen gas production distribution and use, carbon capture and utilisation or storage (CCUS), biorefineries, process integration (including energy efficiency), industrial symbiosis, Artificial Intelligence and Machine Learning, digitization, new business models, circular economy and lastly, changes due to evolving changes in consumer behaviour.

NOTES FOR A GUIDELINE FOR STIMULATING BIOFUELS DEVELOPMENT

Different other projects have investigated experiences and possible drivers and barriers for biofuels and tried to provide guidelines for decision makers. Merging the results of e.g. [ADVANCEFUEL 2020], [Panoutsou 2021], [E4tech 2015], [EBTP 2015] and [IRENA 2019] and with the results of this lessons learned study, a summary of “good to know” aspects for decision makers from policy and industry is given in Table 2. The table is structured along the value chain from resource to fuel delivery. Often not considered in an appropriate way is also capacity building in terms of education and training of the required skilled personnel along the value chain.

Table 2 Guideline aspects (without claiming to be comprehensive)

Value chain aspect	Recommendations esp. relevant for industry	Recommendations esp. relevant for policy
Resource mobilisation | Cropping incl. soil quality and carbon as well as improve degraded land, mobilise residues and organic waste	Roll out of new innovations Show multi-purpose benefits arising from resource mobilisation for a (circular) bioeconomy Develop residual biomass supply chains and efficient mobilisation Support technology transfer and knowledge exchange with other biomass sectors	Define of uniform definitions and classifications in relevant regulations Monitor of land / resource ownership and land / resource management Promote of knowledge transfer Support of initiatives for domestic resources, innovative crop rotation schemes, rural land use planning (incl. financial) Clarify sustainability requirements and certificates Map local potentials and promote rural areas valorisation
Resource logistics | Infrastructure for efficient and timely mobilisation of resources	Improve/develop technologies for dedicated domestic resources acc. to their specific properties Build up regional hubs for resource logistics	Support for R&D&D to improve/develop technologies for dedicated domestic resources acc. to their specific properties Promote regional infrastructures for resource hubs
Biofuel production technologies | General	Support appropriate feasibility studies for biofuel projects including e.g. technical aspects (plant design, resource and product markets and their development as well as impacting factors), relevant norms, standards, certification schemes, permitting strategy, the timeline, costs and environmental issues, risk management aspects, communication strategy around sensitive issues Be open for capacity building, knowledge sharing and public-private partnerships to accelerate progress in TRL/FRL Share knowledge along the whole value chain and esp. considering also respective (life)time frames of the different fuel-infrastructure-powertrain routes	Provide research and innovation grants to ensure continuity in funding to overcome technical barriers and improve innovations Set a frame for funding schemes and financial institutions to increase budget shares in their investment portfolios Set tailored financing mechanisms (e.g. quotas, premiums, penalties) to develop a secure framework to reduce capital investment (CAPEX) and uncertainties of production costs (OPEX) Support R&D&D networks of industry and academia allowing to accelerate progress in TRL/FRL for both WTT and TTW

Value chain aspect	Recommendations esp. relevant for industry	Recommendations esp. relevant for policy
Infrastructure and trade | Broader fuel portfolio	Support an active role of traders to promote different biofuel options for different applications Work on awareness, investments in and operation of different fuel infrastructures (e.g. gaseous fuels like methane and hydrogen as well as drop-in fuels)	Support to increase acceptance (e.g. public knowledge transfer of fuel-powertrain routes incl. sustainability aspects)
Appropriate norms and standards for innovative technologies	Start normalization and standardization activities in parallel to TRL/FRL for pilot and demonstration in order to be ready for the market	Support of accompanying projects to support normalization and standardization activities as well aspects with regard to methodologies, analytical requirements etc.

In addition to that the key results of this lessons learned biofuels study IEA AMF Task 59 have conducted a study on "Lessons Learned from Alternative Fuels Experience". Motivation for this task was that despite many countries are actively seeking to increase the share of renewables in transport, experiences with various attempts to introduce alternative fuels and vehicles has shown that this is not always of success. IEA AMF concluded: "For the successful implementation of alternative fuels and vehicles in the transport system there is the need for long-term and comprehensive policies which include markets, stakeholders and different technologies to gain benefits for all types of stakeholders along the value chain."

4. Conclusions

To answer the two research questions of this project on "Lessons learned biofuels" the most important key messages are:

- Ambitious strategies and targets do not automatically create a frame that allows increasing or building up innovative technologies along the well-to-wheel/wake chain. The case studies for advanced biofuels have showed technical success however not the required commercial success. To achieve this, harmonised technology push and market-pull policies and a comprehensive monitoring of their impacts are necessary as well. This also include steering instruments to secure financing in order to lower the risk of investments and plant operation.

- Moreover, decarbonisation of the transport sector needs a transition process that allow starting with promising technology options, allows gaining experience and learning lessons for continuous improvement. We don´t have time to wait for optimized options that might fulfil all SDGs from a very early beginning.

- Therefore, it is necessary to continuously work on harmonised clear long-term policies that allow improvement of established biofuel options as ground base for decarbonisation in transport. At the same time R&D&D on innovations of advanced biofuels including hybrids with other renewables that are more complex and thus (usually) more cost demanding (e.g. with regard to GHG mitigation) is urgently needed for a sustainable carbon neutral world.

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Abbreviations

2G	second generation (or advanced)
BTL	Biomass to liquids
BTX	Biomass to synthetic product
CAPEX	Capital expenditure
CCUS	Carbon capture and use or storage
CFD	Contract for difference
DME	Dimethyl ether
EJ	Exajoule
EU	European Union
FAME	Fatty acid methyl ester
FRL	Fuel readiness level
GHG	Greenhouse Gases
HEFA	Hydrotreated esters and fatty acids
HVO	Hydrotreated Vegetable Oil
IEA	International Energy Agency
ISCC	International Sustainability and Carbon Certification
KIT	Karlsruhe Institute of Technology
LCA	Life Cycle Assessment
LUC	Land use changes (I for indirect, D for direct)
OPEX	Operational expenditures
PJ	Petajoule
PTX	Power to synthetic product
R&D&D	Research & Development & Demonstration
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuel

SDS	Sustainable Development Scenario
SDG	Sustainable Development Goals
SNG	Biosynthetic Natural Gas
TCP	Technology Collaboration Program
TRL	Technology Readiness Level
TTW	Tank to wheel
US	United States of America
WP	Work Package
WTT	Well to tank

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

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