The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

D5.3 Market study on DME

Subtasks:

T5.2.1 Market Analysis

T5.2.3 Regulatory compliance and standardisation

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Technical References

Project Acronym	CO2Fokus
Project Title	CO_2 utilisation focused on market relevant dimethyl ether production, via 3d printed reactor - and solid oxide cell-based technologies
Project Coordinator	VITO (Vesna Middelkoop)
Project Duration	42 months

Deliverable No.	D5.3
Dissemination Level	Public
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Task	T5.2.1 Market Analysis T5.2.3 Regulatory compliance and standardisation
Lead beneficiary	LGI
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Abbreviations and acronyms

Acronym	Description
ACEA	European Automobile Manufacturers Association
APV	Alternatively-Powered Vehicle
ASTM	American Society for Testing and Materials
BEV	Battery Electric Vehicle
BP	British Petroleum
BRGM	Bureau de Recherches Géologiques et Minières
C&I	Commercial and Industrial
CAPEX	Capital expenses
CatVap	Catalytic Evaporation
CBG	Compressed Biogas
CEO	Chief Executive Officer
CGCL	Caribbean Gas Chemical Limited
CIS	Commonwealth of Independent States
CO	Carbon monoxide
CO_2	Carbon dioxide
CCS	Carbon capture storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture utilisation and storage
CNG	Compressed Natural Gas
DME	Dimethyl ether
EC	European Commission
ECE	Economic Commission for Europe
ECV	Electrically Chargeable Vehicle
EEA	European Economic Area
EJ	Exajoule
EOR	Enhanced Oil Recovery
EU	European Union
EUDC	Extra Urban Driving Cycle
EU ETS	Emissions Trading System
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FPT	Fiat Powertrain Technologies
GCW	Gross Combination Weight
GHG	Greenhouse gas emissions
H2	Hydrogen
HDV	Heavy Duty Vehicle

HGL	Hydrocarbon Gas Liquids
HVO	Hydrotreated Vegetable Oil
IDA	International DME Association
IEA	International Energy Agency
ISO	International Standards Organisation
JDA	Japan DME Association
Kg	Kilogram
KM	Kilometers
kPa	Kilopascal
KT	Kiloton
KWH	Kilowatt-hour
LBG	Liquefied Biogas
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Energy
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
m^3	Meter cube
MDSP	Minimum DME Selling Price
MENA	Middle East and North Africa
MJ	Megajoule
Mg	Milligram
Ml	Millilitres
MSW	Municipal Solid Waste
MTG	Methanol to gasoline
MTO	Methanol toolefine
n.d	No date
NECP	National energy and climate plans
NEDC	New European Driving Cycle
NGO	Non-governmental organisation
NOx	Nitrogen oxides
OPEX	Operating expenses
PESTEL	Political Economical Societal Technological Environmental Legal
RED II	Renewable Energy Directive
rDME	Renewable Dimethyl ether
RDF	Refuse Derived Fuel
ROI	Return on investment
R&D	Research & Development
SME	Small Medium Enterprise

SOx	Sulphur Oxides
TEN-E	Trans-European Networks Energy
THC	Total Hydrocarbon Content
TRL	Technology Readiness Level
UK	United Kingdom
US	United States
WLPGA	World LPG Association
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
ZLEV	Incentive mechanism for zero- and low-emission vehicles

Glossary

Term	Description
Autogas	Autogas is the name used for LPG (liquefied petroleum gas) when it's used to power vehicles.
Biodiesel	Biodiesel is a renewable, biodegradable fuel made from various vegetable oils, animal fats and recycled restaurant greases. It is produced through a chemical process called transesterification. Glycerine is separated from the fat and vegetable oil. Palm oil based biodiesel is the most commonly used form. Biodiesel can be mixed with conventional diesel **(Volvo, 2015)**.
Carbon capture and utilisation (CCU)	Carbon capture and utili**sation** (CCU) is the process of capturing carbon dioxide (CO_2) to be recycled for further usage **(Rosa Cuéllar-Franca, 2015).**
Catalyst	Substance that increases the rate of a chemical reaction without itself undergoing any permanent chemical change **(Cambridge Dictionnary, 2022)**
Decarbonisation	Decarbonisation is the reduction of carbon dioxide emissions using low carbon power sources, achieving a lower output of greenhouse gases into the atmosphere **(TWI Global).**
Deffossilisation	The implementation of measures and techniques in an industry or sector of activity to limit the use of fossil fuels as an energy source **(Office québécois de la langue française, 2021).**
Dimethyl ether (DME)	Dimethyl ether (DME) is a colourless gas with a faint ethereal odour with the formula CH_3OCH_3. It is shipped

	as a liquefied gas under its vapor pressure. **(National Library of Medicine, 2022).**
Drop-in biofuels	Liquid bio-hydrocarbons that are functionally equivalent to petroleum fuels and are fully compatible with existing petroleum infrastructure **(Van Dyk, 2019)**
E-fuel	Electro fuels or e-fuels are an emerging class of carbon-neutral drop-in replacement fuels that are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. They are a sustainable solution for the aviation, maritime and road transport **(Siegemund, 2017).**
Electrification	Electrification refers to the process of replacing technologies that use fossil fuels (coal, oil, and natural gas) with technologies that use electricity as a source of energy **(Cleary, 2022).**
Ethanol	Ethanol is an organic chemical compound with the chemical formula C_2H_6O. It is a flammable and volatile colourless liquid and when used as a renewable fuel, it can be made by fermenting crops that contain starch or sugars. Currently, corn, wheat and sugarcane are the most predominant crops for producing ethanol. Waste from paper mills, potato processing plants, breweries and beverage manufacturers can also be used **(Volvo, 2015).**
Fossil energy	Fossil energy sources, including oil, coal and natural gas, are non-renewable resources that formed when prehistoric plants and animals died and were gradually buried by layers of rock **(US Department of Energy, n.d).**
Hydrogen	Hydrogen is a colourless, odourless, flammable gas that combines chemically with oxygen to form water **(Dictionary.com, n.d)**. Used as a fuel, hydrogen is a clean fuel that, when consumed in a fuel cell, produces only water **(Office of Energy efficiency & renewable energy, n.d)**. The terms “blue hydrogen” and “green hydrogen” are commonly used in relation to hydrogen production methods : • Hydrogen made from natural gas must incorporate CCUS into the process to be considered “blue hydrogen” • Hydrogen generated from renewable energy sources is considered “green hydrogen” **(Energyfactor Europe, 2021)**

Hydrotreated Vegetable Oil (HVO)	Hydrotreated Vegetable Oil (HVO) is a paraffinic bio-based liquid fuel originating from many kinds of vegetable oils, such as rapeseed, sunflower, soybean, and palm oil, as well as animal fats. It can be used in conventional diesel engines, pure or blended with fossil diesel (petrodiesel) **(Athanasios Dimitriadis, 2018).**
Methane	Methane is a colourless odourless flammable gaseous hydrocarbon CH_4 that is a product of biological decomposition of organic matter and of the carbonisation of coal, is used as a fuel and as a starting material in chemical synthesis **(Merriam-Webster, 2022).**
Methanol	Methanol is a light volatile flammable poisonous liquid alcohol CH_3OH used especially as a solvent, antifreeze, or denaturant for ethanol and in the synthesis of other chemicals **(Merriam-Webster, 2022).**
Point source	Any single identifiable source of pollution from which pollutants are discharged, such as a pipe, ditch, ship or factory smokestack **(US Environmental Protection Agency, n.d).**
Renewable DME / rDME / Bio-DME / Sustainable DME / Green DME	Renewable DME can be produced from a wide range of sustainable feedstocks: Sewage sludge, renewable power + CO_2, agriculture residues and energy crops, forest residues, animal waste and municipal waste **(SHV Energy, International DME Association, 2020).**
Traditional DME	Most traditional/fossil DME is produced from methanol, which is produced from natural gas and coal.
Solid oxide electrolyser cell	A solid oxide fuel cell that runs in regenerative mode to achieve the electrolysis of water (and/or carbon dioxide) by using a solid oxide, or ceramic, electrolyte to produce hydrogen and oxygen **(Institute for Sustainable Process Technology , 2022).**

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Executive Summary

CO2Fokus is a combination of innovative technologies synthetising carbon dioxide captured from industrial emissions and green hydrogen, in order to produce rDME (renewable dimethyl ether).

While the current DME market is mainly focused on the use of this molecule as a chemical solvent or aerosol propellant, the present deliverable (Market study) explores other market opportunities of rDME, such as the replacement of diesel in vehicles (e.g. trucks, agricultural and construction vehicles); blending with LPG (liquefied petroleum gas); and use as a hydrogen carrier.

When used as a fuel (for diesel replacement and Autogas applications), rDME is clean and can contribute to defossilisation and decarbonisation. The combustion process of DME contributes to lower greenhouse gas emissions and its use significantly reduces SOx, NOx and soot emissions compared to diesel. Additionally, only modest modifications are required to a vehicle's engine and fuel system in order to use rDME as a fuel in vehicles (for example in trucks), with no need to replace current vehicles, and existing LPG infrastructure can serve to distribute DME. Despite the great potential and cleanliness of DME, the 0 gram CO_2 emission target for 2035 is a barrier to use DME as a fuel in the European market because CO_2 is emitted back (even at lower quantities compared with diesel) when burned.

rDME can also be blended with LPG. This use contributes to considerably clean gas that can be used for commercial and domestic transportation, cooking and heating. At one time, LPG-DME blends were widely used for cooking and heating applications in China, and this Market Study also considers DME and LPG blends in other geographical markets and for other applications. A third possible market opportunity, is the use of rDME as a hydrogen carrier, to transport a larger quantity of hydrogen from point A to B, using LPG infrastructure.

To get a comprehension of the global DME market and analyse market opportunities of renewable DME for applications such as diesel replacement, LPG blends and as a hydrogen carrier, LGI interviewed over 30 leading global DME experts to get exclusive insights shared in the present deliverable.

It appeared that while the cleanliness of rDME was proved in many ways by researchers across Europe, North America and Asia, this molecule has never gained any attention from the public. If rDME is still looking for its way to get to the market, political and regulatory steps are critical to allow its use as a fuel or for LPG blends, and the development of the hydrogen economy is necessary for the use DME as hydrogen carrier.

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1 Introduction

The Horizon 2020 CO2Fokus project aims to participate in the promotion of a low carbon economy and to develop an innovative route for CO_2 utilisation into a valuable product - dimethyl ether - by building and combining scalable commercial technologies. Therefore, technology partners involved in the CO2Fokus project include those developing modular technologies capturing carbon from industrial emissions, producing green hydrogen and synthesising carbon dioxide and hydrogen into DME.

Work Package 5's (WP5) objective is to coordinate the dissemination and exploitation activities. The subtask 5.2.1'sobjective is to gain detailed insights on the market potential of DME and the subtask 5.2.3 aims at verifying if the project outputs comply with the industry standards.

The present deliverable (D5.3), "Market Study," presents results of both subtasks 5.2.1 and 5.2.3 which together will feed in the exploitation deliverable (D5.5) due in the first semester of 2023.

Understanding the DME market is a necessary step to prepare the market entry and exploitation of CO2Fokus technology. This market analysis is based on a literature review with more than 45 references, on one-to-one qualitative interviews with over 30 international DME experts and on inputs collected during the DME 9 Conference organised by the International DME Association in Zurich in June 2022.

The present deliverable analyses:

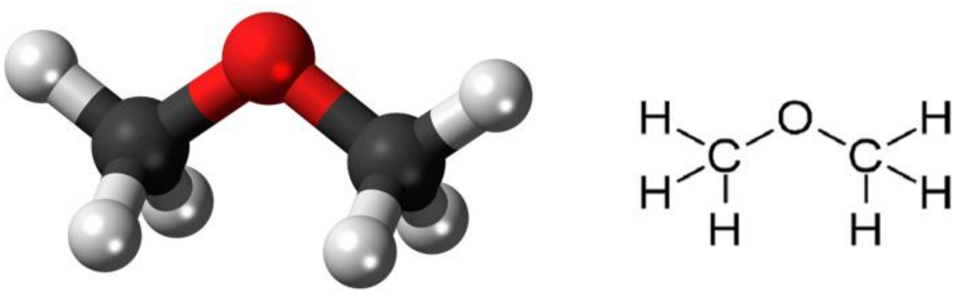
- The macroeconomic environment, presenting a global market sizing, geographical markets and a comprehensive PESTEL and Regulatory study,
- The DME industry, through a market opportunities delimitation and characterisation (by DME segment), a demand analysis and a detailed benchmark of the current DME players in the world.

1.1 Context

1.1.1 Renewable DME introduction

Dimethyl ether (DME) is a single molecule that is a gas at room temperature and pressure, and is chemically similar to propane and butane (Figure 1). DME has been used for over 50 years in the chemicals sector, primarily as an aerosol propellant and as a solvent. More recent usages have highlighted the potential of DME for the transport sector as a sustainable alternative for diesel replacement in medium- and heavy-duty on- and off-road vehicles (HDVs),, for blending with LPG and as a hydrogen carrier.

Figure 1: Dimethyl ether molecule and chemical formula (Air Liquide, 2022)



[1]

[1] *H= Hydrogen, C=Carbon, O = Oxygen*

DME can be produced in several different ways and is categorised in two types: **Traditional DME** and **Renewable (or Bio) DME**.

- Most **Traditional DME** is produced from methanol, produced from natural gas and coal. DME is a common by-product of methanol production.
- **Renewable DME (rDME)** can be produced from a wide range of sustainable feedstocks including sewage sludge, renewable power and CO_2, agriculture residues and energy crops (for example sugarcane waste), forest residues, animal waste and municipal waste, as illustrated in Figure 2 (SHV Energy, International DME Association, 2020). According to Fleisch, there are two possible production pathways for rDME (Fleisch, 2022):
    - **For sustainable feedstocks,** rDME can be produced from gasification, bio-gas reforming or syngas to methanol
    - **For CO_2 hydrogenation (e-DME),** it can be produced from waste CO_2 streams, CO_2 capture from air, green H_2 from water and e-methanol (CO_2 derived methanol, solar or wind).

Figure 2: Renewable DME can be produced from a wide range of sustainable feedstocks (SHV Energy, International DME Association, 2020)

1.1.2 E-fuels definition

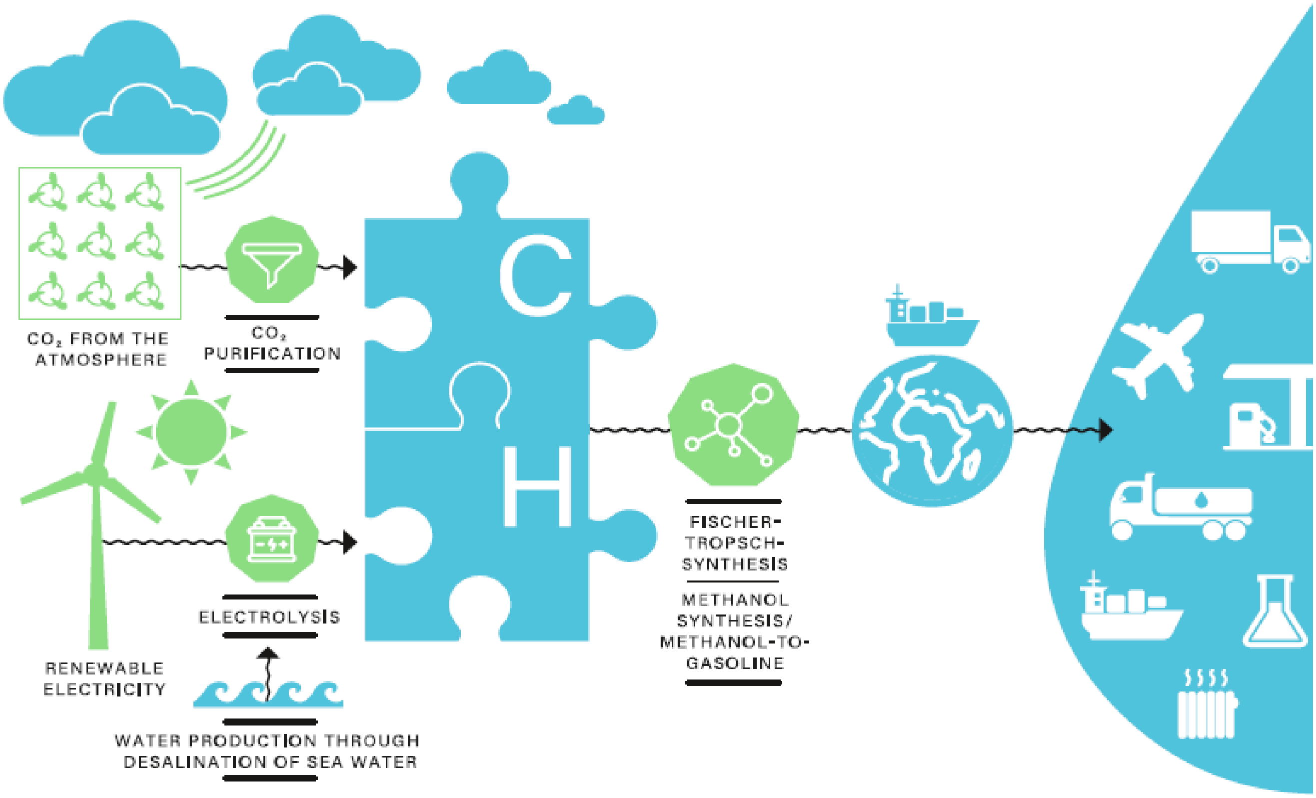
E-fuels are synthetic fuels produced by synthesising carbon and hydrogen. The production of e-fuels requires electricity from renewables. As such, rDME can be considered an e-fuel.

The production of e-fuels follows the process described in Figure 3:

- Extraction of hydrogen from water by electrolysis using renewable electricity;
- Hydrogen and CO_2, directly captured from the atmosphere, are converted into a liquid energy carrier, by using for instance the Fischer-Tropsch synthesis;
- Power-to-Liquid (PtL): renewable electricity is converted into a synthetic, multi-purpose fuel with drop-in ability.

The rDME production process appears carbon neutral as no additional greenhouse gases are produced (Ralf Diemer e. A., 2022).

Figure 3: Production process of e-fuels (Ralf Diemer e. A., 2022)



E-fuels offer the promise of being part of the range of solutions deployable to help tackle climate change, however today the current production costs remain high: In 2025, the production costs for one litre of e-fuel (with a 4% blending rate with conventional fuels) are estimated to be between EUR 1.61 and EUR 1.99 while diesel will cost around EUR 1.22 for customers at filling station (eFuel Alliance, 2022).

According to efuel Alliance, Prognos AG study, the Fraunhofer Institute UMSICHT and the German Biomass Research Center (DBFZ), "*Economies of scale will reduce the production cost of efuels … while in the meantime the share of blending is steadily increased. The production costs are assumed to be less than EUR 1 per litre in 2050. Climate neutrality thus remains affordable for everyone.*"

1.1.3 CO_2Fokus technology overview

CO_2Fokus aims to make a significant contribution to the fight against climate change and transition to a low-carbon society. The CO_2Fokus project focuses on the utilisation of industrially emitted CO_2 for the economically and environmentally viable direct production of DME and its subsequent use. The technology includes 3D printed catalysts, multi-channel catalytic reactors and solid oxide electrolyses cells to produce DME in an efficient way. The process relies on the hydrogenation of industrially emitted CO_2 using hydrogen produced through electrolysis.

CO_2Fokus project has a number of stated technical and business objectives to achieve:

- Replacing fossil fuels;

- Storing seasonal energy;
- Upscaling in the short to medium term

Main project expected impacts:

- *Conversion of captured CO_2, for example using hydrogen made from renewable energy, to produce fuels. This is not only a means to replace fossil fuels, but also a promising solution for seasonal energy storage.*
- *Project expected impact: Development of energy efficient and economically and environmentally viable CO_2 conversion technologies for chemical energy storage or displacement of fossil fuels that allow for upscaling in the short to medium term.*

However, there are challenges to overcome to achieve these objectives:

- Utilisation of CO_2 limited by its low energy content;
- Conversion process highly energy intensive;
- Scalability of the 3D printing reactor;
- There are still relevant and significant scientific and technological challenges to be able to exploit the CO_2 as a chemical and fuel feedstock in a systematic manner, the main challenge being that the chemical utilisation of CO_2 is limited by its low energy content, and the conversion process is highly energy intensive.

1.1.4 CCU market context

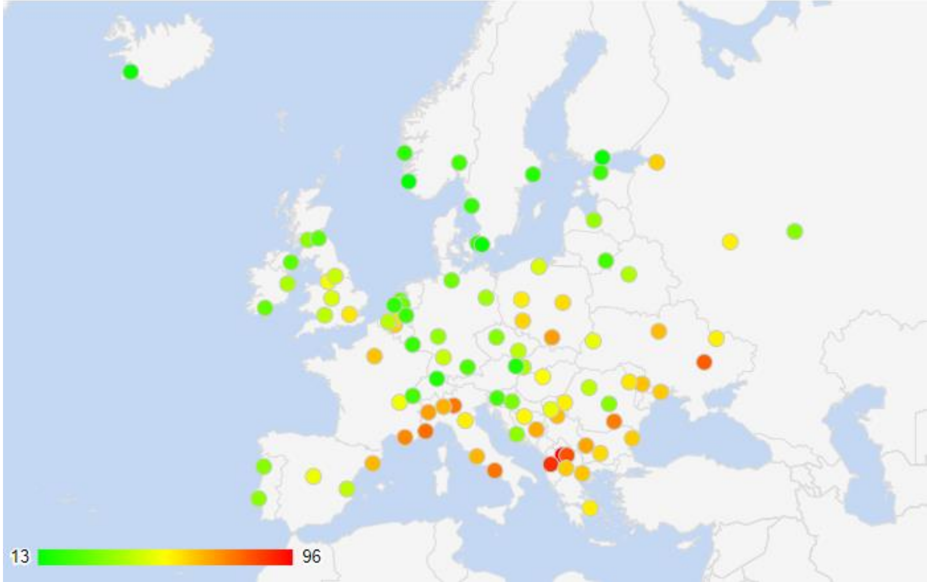
First, some of the most polluted and important industrial regions in Europe are listed in order to identify some potential market opportunities for the CO_2Fokus technology, and specific geographical locations where the CO_2 capture appears to be the most critical. The maturity of the Carbon Capture and Utilisation (CCU) market is then studied based on the stage of current CCU projects in Europe.

Most polluted countries and regions in Europe

Turkey is the European country with the highest pollution (HEAL, 2017). Poland is the second most polluted European country, notably because of the number of coal-fired power plants in South Poland. Other places and countries among the highest pollution levels include Russia, Latvia and North Macedonia, (more specifically the districts of Tetovo and Skopje) (Numbeo, 2022) (GEO, 2019). Figure 4 outlines the pollution index[2] in major European cities in 2022.

[2] *Pollution Index is an estimation of the overall pollution in the city. The biggest weight is given to air quality. Water pollution/accessibility is also considered. This data is sourced from the World Health Organisation.*

Figure 4 Pollution index by city (Numbeo, 2022)



In Western and Southern Europe, Italy's Po Valley is also among the most polluted regions of the continent (GEO, 2019). In France, the most polluted places include: the Arve Valley, the Rhine Valley, the Meuse Valley, the Pond of Berre near Marseille, and industrial sites in the cities of Grand-Quevilly, Sallanches in Upper Savoy, or the industrial zone of Inspira in Salaise-sur-Sanna (Andréani, 2019) (Cerinsek, 2019) (Roussel, 2020). In Belgium, Antwerp, Ghent and Anderlecht can be highlighted (La Libre, 2013).

Most important industrial sites/regions in Europe

Figure 5: Manufacturing centers in Western Europe (Chand, nd)

The main manufacturing zone in Western Europe extends from the UK through Northeastern France, Belgium to the Rhineland of Germany. Other important industrial areas are found on the Swiss Plateau, Northern Italy, and in many large cities throughout Europe such as London, Paris, Berlin and Milan (Figure 5).

In the UK, the Northeast coast industrial region includes coal field exploitation: Durham and Northumberland, Cumberland and Westmorland, the West Riding of Yorkshire, Nottinghamshire and Derbyshire, Lancashire, the Birmingham Region (Midlands), Greater London, Port Talbot and Newport in South Wales, the Clyde, Ayrshire, Midlothian and Western Fife in Scotland.

In Germany, the Rhine Industrial Region, the Middle Rhine Industrial Region, the Hamburg Industrial Region, the Berlin Industrial Region and the Leipzig Industrial Region rank among the highest polluters.

In France, The Northeast Industrial Region, Lorraine Industrial Region, Metz-Thionville complex in the Moselle valley, the Greater

Paris Basin, Central Plateau Industrial Region, Rhone Sone Valley Region, Mediterranean Industrial Region are the most critical (Chand, nd).

CCU projects in Europe (or industrial zones with CCU/CCUS sites already implemented)

In Europe, Carbon Capture and Storage (CCS) technologies and projects are currently more advanced than CCU projects, which are much rarer (Global CCS Institute, 2020). Examples of CCU (and CCUS) projects include:

- **North CCU hub:** Since 2018, twenty public and industrial partners in the port area of North Sea Port have joined forces, collectively known as the North-CCU-hub, to reduce CO_2 emissions by focusing on new developments for the capture and reuse of CO_2. The North-CCU-hub will develop new circular value chains in which CO_2, emitted by industry, can be used as a raw material. Transforming CO_2 into high value products with commercial value including e-fuels such as green methanol and ammonia, but also higher value chemicals such as fatty acids, proteins and esters is in the scope of the North CCU Hub project (North CCU Hub, n.d).
- **Power-to-Methanol Antwerp BV:** The Power to Methanol project in Antwerp will produce methanol from captured CO_2 combined with hydrogen that has been sustainably generated from renewable electricity (Power to Methanol Antwerp BV, n.d).
- **ArcelorMittal and LanzaTech CCUS project in ArcelorMittal's industrial site in Ghent, Belgium:** The technology licensed by LanzaTech uses microbes that feed on carbon monoxide to produce bioethanol, which will be used as transport fuel (ArcelorMittal, n.d)**.**
- **LafargeHolcim and Carbon Clean to develop large scale CCUS plant**: Based in the company's cement plant in Carboneras (Almeria, Spain), the project will aim to capture CO_2 emitted through the cement production process to be further transformed, cleaned and reused locally. The CO_2 will be captured from the cement plant's flue gas and recycled for agricultural use for accelerated crop production (Carbon Clean, 2020).
- **Project Air:** Perstorp, a Swedish chemical company, will build a CCU plant in Stenungsund, Sweden that will convert carbon dioxide emissions captured from Perstorp's operations as well as other residue streams, biogas and renewable hydrogen to methanol (Project Air, n.d).
- Based in the Netherlands, **RealCarbonTech** has a patented technology which offers direct conversion of CO_2 into marketable methanol-based products for energy, chemical or transportation sectors. Methanol and DME are key products resulting from their direct synthesis (RealCarbonTech, n.d).

While CCU projects are still at an early stage of development compared to CCS, more and more projects are taking shape across several European countries. Methanol, chemicals and bioethanol figure among the main final products that are created through CCU processes.

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1.2 Methodology

The methodology used in this market analysis report relies on a literature review conducted through a complete desktop search with more than 45 references (see Bibliography), two series of more than 10 qualitative interviews of experts (PESTEL (9) and industry analysis (18)) and complementary data collection at the DME 9 Conference organised by the International DME Association in Zurich in June 2022. All information collected was analysed and synthesised in this report to provide an overview of the market around the CO_2Fokus technology.

1.2.1 Global DME market dynamics

To analyse global trends and gain an understanding of the overall market, a desktop search was conducted with more than 45 references and led to:

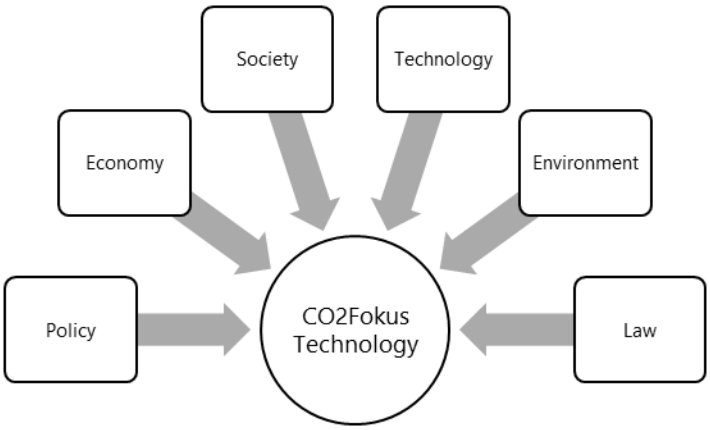
- the mapping of competition benchmark players in the energy, low carbon energy and DME sectors;
- the mapping of the energy sources used in the transportation sector (aviation, cars, trucks, maritime, buses);
- the mapping of current usage of DME;
- the analysis of the demand of DME and for low-carbon energy (including in the transportation sector);
- global DME data feeding all the market analysis report.

1.2.2 PESTEL and Regulatory analysis

The PESTEL (Political Economic Societal Technological Environmental and Legal) analysis methodology was used in this research to identify the main factors critical to the DME and CCU environments. Ten experts were interviewed in order to gain an understanding of the influence of the macro environment on the CO_2Fokus project. The PESTEL analysis also relies on complementary information collected in the second series of interviews with DME experts as part of the industry analysis and during the DME 9 Conference, especially legal and regulatory information from the eFuel Alliance presentation. A transcription of all interviews was made, and the analysis was led and shared with the Consortium.

The PESTEL analysis constitutes a framework of macro-environmental factors described in Figure 6.

Figure 6: Factors impacting the CO_2Fokus technology



- **Political factors** are referring to the analysis of current and forthcoming policies on energy use and trends, geopolitics view of decarbonisation and geopolitical factors.
- **Economic factors** include price volatility, demand for energy, factors for process costs and investment attractiveness.

- **Societal factors** include social acceptance factors of CCU and of energies (fossil fuels/DME), factors of changing paths in society, and social perception of CCU and electrification.
- **Technological factors** include technological concerns and uncertainties, DME storage, transportation/logistical factors to choose a technology, CCU technologies and 3D printing technologies.
- **Environmental factors** include the resources used in the process, public awareness of environmental issues, environmental risks, locations for CCU plants to produce DME, reduction of CO_2 and green DME considerations.
- **Legal factors** are referring to the regulations around DME, CCU and more widely around transportation and renewable energies: EU emission trading system and competitive advantage, legal frameworks to be applied for CO_2Fokus, legal barriers, regulatory incentives, uncertainties and CCU exclusion.

LGI gathered the insights from ten cross-disciplinary experts through qualitative interviews conducted in 2020. The participating experts to the section 1.2.2 PESTEL and Regulatory analysis are listed in Table 1. The deliverable is a result of the analysis of the project team and does not necessarily reflect the opinions of the experts interviewed.

Table 1: List of experts interviewed for the PESTEL analysis

Name of the expert	Position	Organisation	Area of expertise
Anastasios Perimenis	Secretary General	CO_2 Value Europe	Political & Environmental
Anonymous expert	Assistant professor of Social Economic and Organisational psychology	University	Societal
Denis Bossanne	Economist	Royal Dutch Shell	Technological, Economic & Environmental
Diana-Maria Cismaru	PhD in sociology, Full Professor and Head of Public Relations Department	College of Communication and Public Relations at National University of Political Studies and Public Administration	Societal
Fernanda Veloso	Senior Geologist	Bureau de Recherche Géologique et Ministères (BRGM)	Technological & Environmental
Hamid Godini	Researcher	Eindhoven University of Technology	Technological & Economic
Joost Smits	Senior Scientist	Royal Dutch Shell	Technological, Economic & Environmental
Peter Van Os	Senior Project Manager	TNO	Technological & Environmental
Simon Tilling	Environmental lawyer	Steptoe & Johnson	Legal
Stefan Gara	Member	Vienna City Council and Parliament	Political

Finally, based on desktop search, inputs from experts' interviews and presentation during the DME 9 Conference, LGI prepared a policy and regulatory standards mapping presented in the PESTEL and Regulatory analysis section 2.3.

1.2.3 DME industry analysis

For the DME industry analysis, qualitative one-to-one interviews were conducted with seventeen experts knowledgeable of the DME industry and landscape. Their insights were analysed, compared and synthesised in the report along with desktop research to complement the study. Experts interviewed are listed in Table 2. Complementary information was collected during the at the DME 9 Conference organised in Zurich in June 2022 by the International DME Association.

Table 2: List of experts interviewed for the market analysis

Name of the expert	Position	Organisation	Country
Anonymous expert	/	DME producing company	/
Anonymous expert	/	DME producing company	/
Anonymous expert	/	DME producing company	/
Anonymous expert	/	DME producing company	/
Christopher Kidder	Executive Director	International DME Association	USA
Cinch Munson	Vice President, Commercial Development	Oberon Fuels	USA
Gilles Hardy	Head of Turbocharging Solutions	Accelleron	Switzerland
Ivan Kisurin	CEO	Aerosolex	Russia
Lars Martensson	Director of Environment and Innovation	Volvo Trucks	Sweden
Lizzie German	Investment and Technology Manager	Dimeta	Netherlands
Luca Vailati	Business Development Director	Dimeta	Italy
Matteo Carmelo Romano	Professor of Systems for Energy and Environment	Politecnico di Milano	Italy
Ralf Diemer	Managing Director	E-Fuel Alliance	Germany
Stéphane Marie-Rose	Innovation Director	Enerkem	Canada
Tobias Block	Head of Strategy and Content	E-Fuel Alliance	Belgium
Werner Willems	Technical Specialist – Sustainable Fuels Research	Ford Motor Company	Germany
Wonjun Cho	CEO	Bio Friends	South Korea

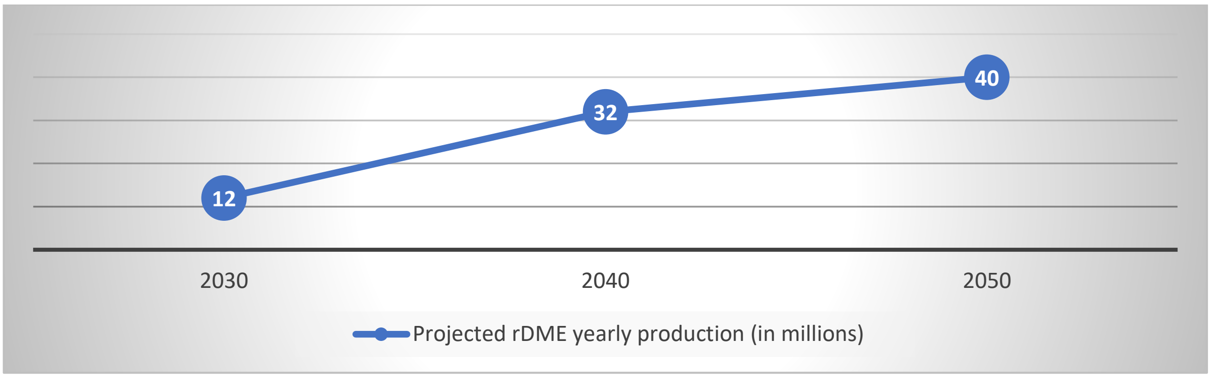
2 Macroenvironment analysis

2.1 DME global market sizing

2.1.1 rDME yearly production by 2030 and beyond

World production of DME in 2019 stands at approximately 9 million tons per annum, and is primarily by means of methanol dehydration (About DME, 2019). According to the WLPGA, future rDME production is expected to considerably increase in the next decades. As shown in Figure 7, the yearly rDME production is expected to reach 12 million tonnes in 2030 and 40 million by 2050.

Figure 7: Projected rDME yearly production (in millions) (Nikos Xydas, 2022)



While there is adequate feedstock availability, it will face competition from other fuels and product intermediates. The availability of rDME is determined by a variety of factors, including production costs and local energy legislation (Nikos Xydas, 2022).

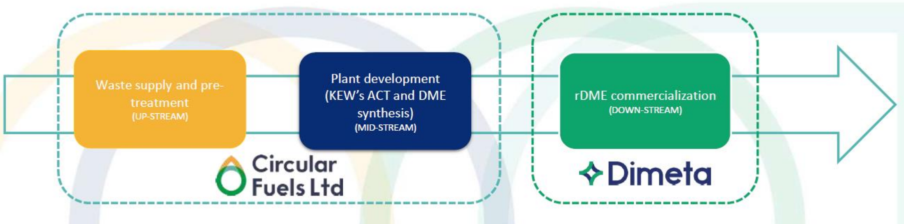
2.1.2 DME players production capacity

According to Aerosolex, the total capacity of EU DME producers is estimated at 150 ktonnes per annum (Kisurin, DME production, supply and market perspectives, 2022). Table 3 describes the known production capacity of some DME market players across the globe. DME and rDME production per market player per year on three continents is also outlined in Figure 9, Figure 10 and Figure 12.

Table 3: DME market players production capacity

Name of the organisation	DME Production capacity
Oberon Fuels (USA)	Oberon Fuels has an rDME plant with a production capacity of 1.5M gal/year **(3,775 tonnes/year).** A new DME commercial plant aims to be developed by 2024, with a 3.5M gal/year **(8,800 tonnes/year)** production capacity. Other plants will then be developed in the next few years, with a standardised design to reduce costs and speed deployment **(Munson, Renewable DME Positioning your company as a sustainability leader, 2022).**
Circular Fuels Ltd (UK)	Circular Fuels Ltd aims to have its first demonstration plant operational by end of 2022 in the UK and its first commercial plant "Circular Fuels Arboretum Limited" to

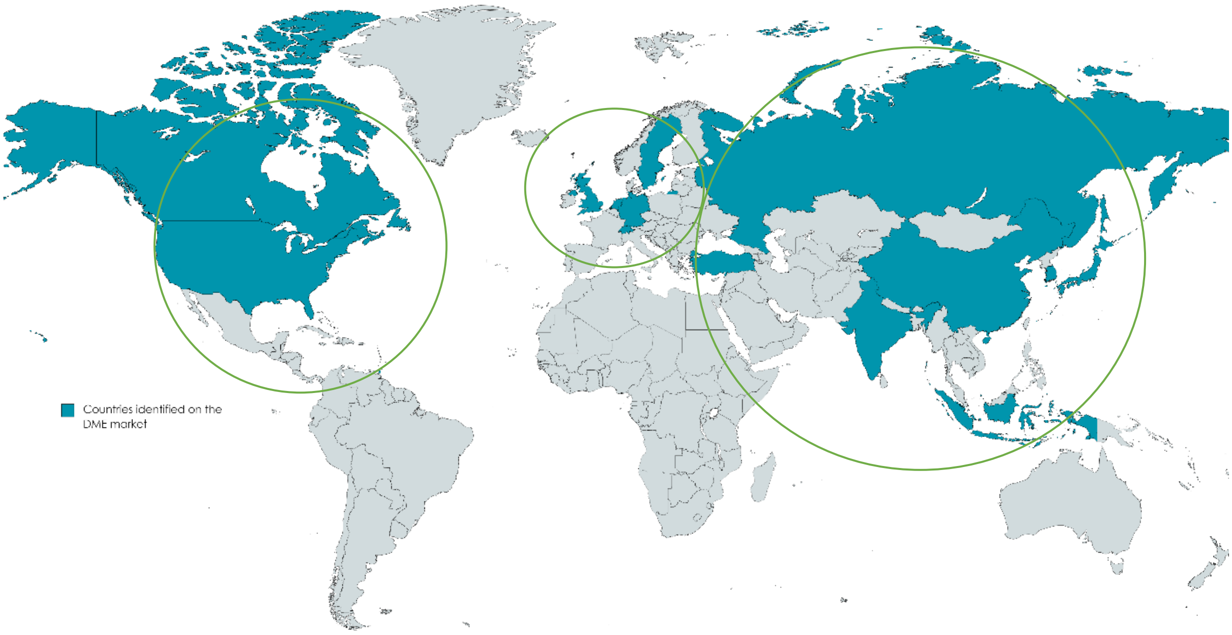
The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Joint venture of Dimeta and KEW Technology Ltd	produce **50,000 tonnes a year** of rDME produced from municipal waste by 2024 **(Cocchi, 2022)**. 
Dimeta (Netherlands) *Joint venture of SHV and UGI*	Dimeta aims to develop more than **300,000 tonnes / year** of rDME capacity for the EU, UK and US markets by 2027. Through the development of partnerships with LPG distribution companies, Dimeta plans to further accelerate the availability of rDME as a fuel **(Jacobsen, 2022)**.
Nouryon (Netherlands)	Nouryon has a DME production capacity of **45,000 tonnes/year (Kisurin, DME production, supply and market perspectives, 2022)**.
PCC (Germany)	PCC SE has a production plant in Russia's Tula region, with an annual capacity of **20,000 tonnes (PCC EU, 2021)**.
Shell (Germany)	Shell has a DME production capacity of **35,000 tonnes/year (Kisurin, DME production, supply and market perspectives, 2022)**.
Grillo-Werke (Germany)	Grillo-Werke has a DME production capacity of **20,000 tonnes/year (Kisurin, DME production, supply and market perspectives, 2022)**.
Tarkim (Turkey)	Tarkim has a DME production capacity of **20,000 tonnes/year (Kisurin, DME production, supply and market perspectives, 2022)**.
Aerosolex (Russia)	Aerosolex has a production capacity of **10,000 tonnes** high-quality DME (99.999% purity) per year, with a plant located in the industrial area of Dzerzhinsk, Nizhny Novgorod region **(Aerosolex, n.d)**.
CGCL Caribbean Gas Chemical Limited (Trinidad & Tobago) / Mitsubishi Gas Chemical Co (Japan)	Mitsubishi Gas Chemical Co, in collaboration with CGCL has a DME plant in Trinidad and Tobago with an annual production capacity of one million tonnes of methanol and **20,000 tons** of DME at the Union Industrial Estate, La Brea, Trinidad **(Randhir Ramjattan, 2022) (Mitsubishi Corporation, 2015)**.
Bio Friends (South Korea)	Bio Friends has a **5,000 tonnes** DME production plant since 2020, with production dedicated to the Korean aerosol refrigerant and fuel market. In a second factory that aims to be completed in early 2023, Bio Friends is set to produce **6,500 tonnes** of DME from 10,000 tonnes of methanol produced from CO_2 **(Cho, DME, rDME and H2 Business in Korea, 2022)**.

2.2 DME geographic markets

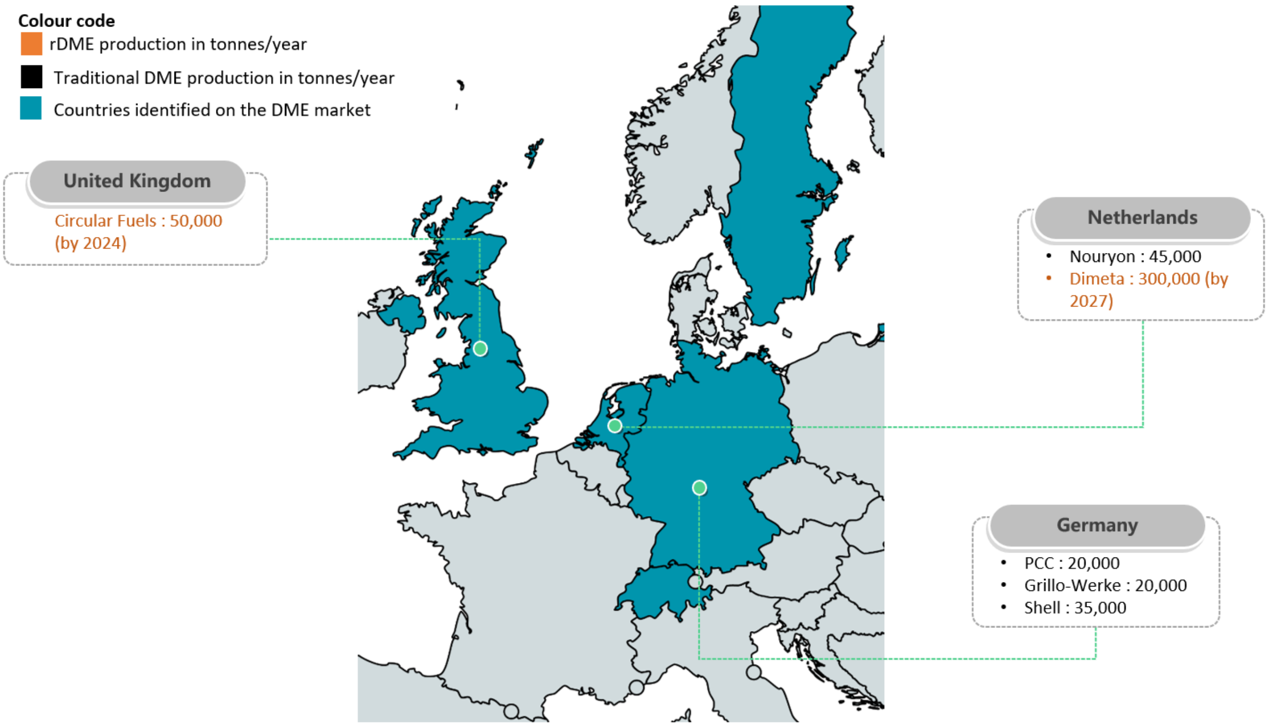
DME stakeholders and DME production is spread around the world. In the following section, a focus will be made on countries that are critical to the global DME production and supply. In some locations, DME projects were initiated in the early 2000's but never came to fruition. The full list of DME market players identified is in Section 3.2 DME market players. Figure 8 outlines the countries with identified stakeholders on the DME market at global scale. There are three major geographical zones with DME production: North America, Western Europe and Asia, surrounded in green and described further in Figure 9, Figure 10 and Figure 12.

Figure 8 Countries present on the DME market around the world



Europe

Figure 9 Countries present on the DME market in Europe and known DME production capacity



- **Sweden**

In 2009, Sweden saw the world's first Bio DME production plant at the Smurfit Kappa paper mill in Piteå (ETIP Bioenergy, 2010).

- **Switzerland**

The 9th international DME Conference in 2022 took place in Zurich, Switzerland. This location was chosen due to a major investment and innovation project development happening there, with Fiat Powertrain and the Swiss federal research facility doing key engine work on heavy duty diesel engines running on DME (Kidder, 2021) (FPT Fiat PowerTrain Technologies, 2021).

- **Germany**

There are several DME and rDME market players in Germany including Linde, PCC and Grillo-Werke. The first rDME filling station was also created in Germany (Aachen).

- **UK**

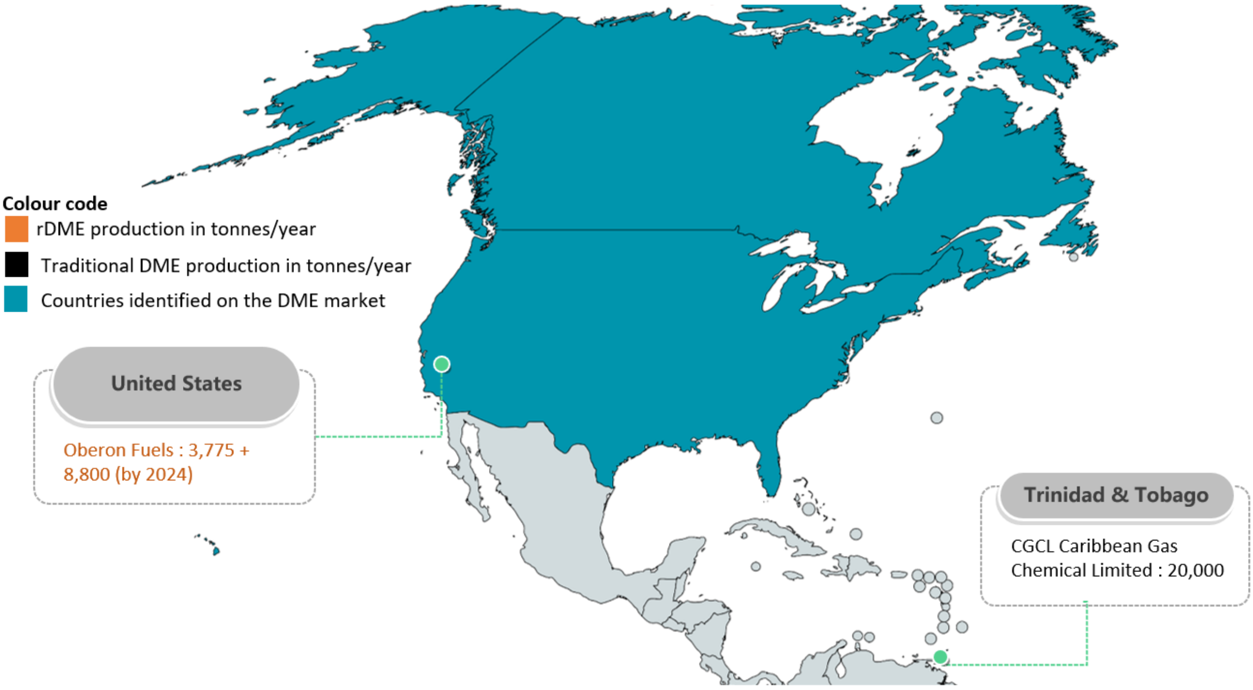
Circular Fuels Ltd, a joint venture of Dimeta and KEW technology Ltd, aims to have its first demonstration plant operational by mid-2022 in the UK (Cocchi, 2022).

- **Netherlands**

A joint venture of SHV and UGI (Dimeta) is established in the Netherlands and projects to expand in Europe by building additional plants. Nouryon is also a major player in the Dutch DME market.

America

Figure 10 Countries present on the DME market in North America and Caribbean and known DME production capacity



- **USA**

Oberon Fuels is the first producer of both fuel-grade DME and rDME in the United States. Figure 11 shows their facility, operational in California since 2013. In the US and Canada, the production, retail sale and use of DME as a fuel is legal.

(Kidder, 2021). In California, a 2020 state legislature passed a bill that defined the tax rate for DME used as either a diesel replacement or blended with propane:

- from $0.18 to $0.06 per gallon of DME;
- and $0.06 per gallon of DME-propane fuel blend.

Such legislation helps to remove barriers to fleet adoption of DME in California and potentially other regions.

Figure 11: Oberon Fuels' pilot rDME production plant in Brawley, California

- **Canada**

Enerkem, a world-leading waste-to-biofuels and chemicals producer based in Montréal, Canada, produces rDME based on bio-methanol. So far, the rDME is not commercialised and kept for internal use only but the company intends to further develop and optimise this opportunity while evaluating its potential commercial applications, including in the transportation sector (Marie-Rose, 2021) (Il Bioeconomista, 2018).

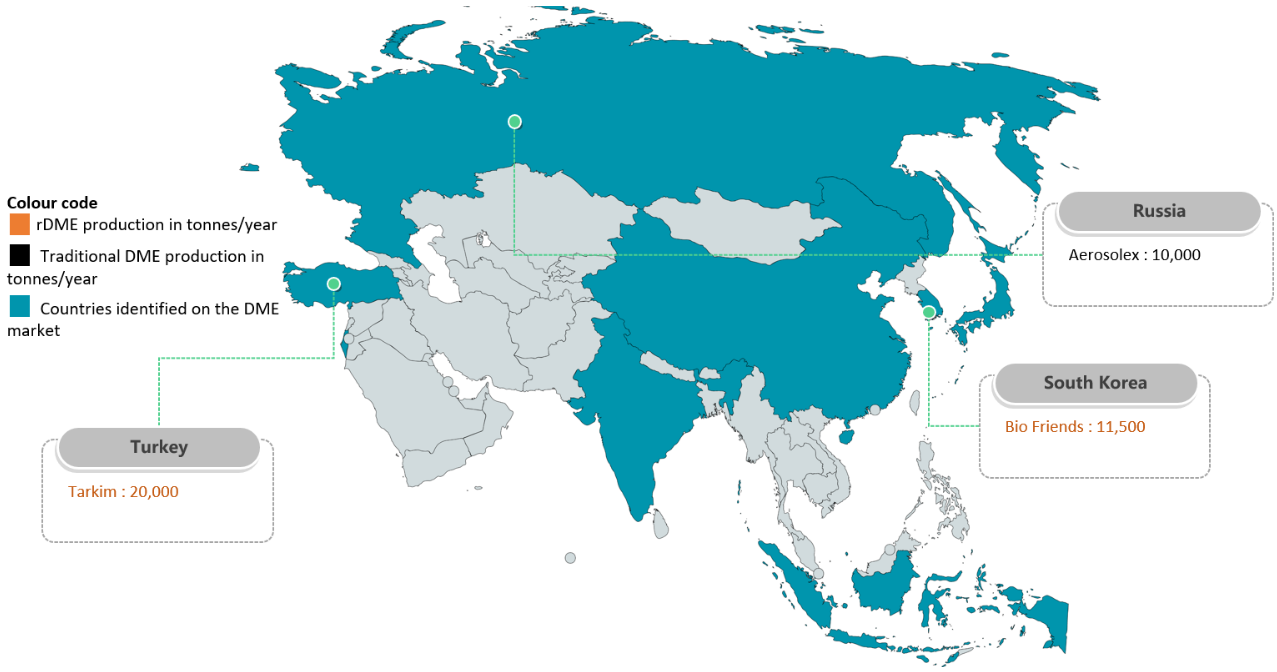
- **South America and Caribbean**

There is only one producer of DME in South America/the Caribbean. CGCL (Caribbean Gas Chemical Limited) is the consortium established to build the plant and oversee the project; NGC (the National Gas Company of Trinidad and Tobago Limited) is the producer and seller of the product. Both are based in Trinidad and Tobago. Traditional DME based on natural gas is produced (Randhir Ramjattan, 2022).

According to IDA Executive Director Christopher Kidder, DME offers a promising option for reducing emissions from the large number of heavily polluting diesel generators commonly used to produce power in the Caribbean and South America (Kidder, 2021).

Asia and Middle East

Figure 12 Countries present on the DME market in Asia and known DME production capacity



- **Russia**

In Russia, Aerosolex is the main market player of the DME market, serving the markets of Russia, Europe and CIS countries. The market price of DME in the country was 1,000€ per tonne, or 1€ per kilo while diesel fuel is 0.6€ per litre in summer 2021 (Kisurin, CEO Aerosolex, 2021).

Figure 13 Aerosolex DME production plant in Dzerzhinsk, Russia

- **Turkey**

Tarkim is an DME producer based in Turkey, mainly serving the aerosol market.

The interest in renewable DME and in LPG blending, as well as the considerable LPG market are key drivers for the DME market in Turkey. Turkey has the largest LPG market in the world: in 2019, the Turkish LPG market meets an estimated 13% of the country's total demand for automotive fuels and accounts for 76% of Turkey's total LPG consumption (World LPG Association, 2019). Additionally, LPG is a popular automotive fuel in the country (Autogas) and widely available at fuelling stations (Kidder, 2021).

"Turkey is potentially one of the hot spots, where all the stars are aligning for the country to potentially become one of the very first locations where renewable DME as a fuel could truly emerge." (Kidder, 2021).

- **Middle East / Egypt**

Methanex, the world's largest producer and supplier of methanol, was developing a DME plant in Egypt in the early 2000's, but that project however ended due to the political unrest in North Africa and Middle East during the Arab Springs (Green Car Congress, 2007).

- **Japan**

In cooperation with the International DME Association and DME promotion organisations in Asian countries, the Japan DME Association (JDA) promotes DME and studies the requirements and standardisation around domestic and global DME use. It is a network of twelve members, mostly Japanese natural gas and energy providers including Mitsubishi Gas Chemical (Ohno, 2022). MGC's 80,000 TPY DME plant is located in Niigata. The Japanese company RenFuD has recently licensed its technology to KEW Technology for the Circular Fuels Ltd organisation in the UK.

Figure 14: DME 100 tonnes/day demonstration plant and shipment (Ohno, 2022)

- **South Korea**

According to Wonjun Cho, 90% of DME fuel in the Asian market is used to be mixed with LPG (Cho, CEO Bio Friends, 2021).

The Korean Government also made investments in DME: Several organisations including the State-owned company Korea Gas Corporation (KOGAS), had an entire department devoted to DME. They developed a single step process for DME synthesis which was never commercialised (Kidder, 2021).

In Korea, Bio Friends Inc. has established a business model with a carbon neutral objective with the DME business. Their final goal will be to build a rMethanol and rDME manufacturing plant using CO_2 emissions from the cement, steel and petroleum industries (Cho, DME, rDME and H2 Business in Korea, 2022).

- **China**

China was the first country where DME was commercialised in large scale for fuel use applications. A combination of major government projects to encourage and develop a coal-to-chemicals industry in China, a desire to reduce the importation of fuels such as LPG and encourage use of abundant domestic feedstocks such as coal, coupled with favourable economics due to the price of methanol and LPG, facilitated the creation of a large scale production and use of DME as a fuel in the period from 2005 – 2012.. Since that time, China has made major progress in the installation of natural gas pipelines to many places that were previously not served by natural gas, and there's been a heavy emphasis by the Chinese government to develop the network of pipelines and to link communities with natural gas infrastructures as opposed to using bottled fuels like LPG.

In China, 2.6 million tons of DME and LPG blend is used, yet the increase of fuel cell and electric vehicles is decreasing the DME market. China is building multiple nuclear powerplants on the east coast but also LNG fuelled power plants, in the objective of decreasing coal-fuelled powerplants (Cho, CEO Bio Friends, 2021).

- **Indonesia**

The Indonesian government has provided incentives to use traditional DME for DME/LPG blend application. Consequently, the Indonesian market became attractive (Cho, CEO Bio Friends, 2021). In South Sumatra (Indonesia), the construction of a $2.3 billion coal gasification plant, designed to use 6 million tonnes of low rank coal to produce 1.4 tonnes of DME annually was announced with the ambition of reducing Indonesia's LPG import by 1 million tonnes per year (Marquez, 2022). While DME projects have been announced multiple times without much apparent progress, development of a first project appears to be "closer today than it ever has been", according to IDA Executive Director Christopher Kidder. In Indonesia, household use is the primary market as LPG is the dominant fuel used throughout the country for domestic applications (Kidder, 2021).

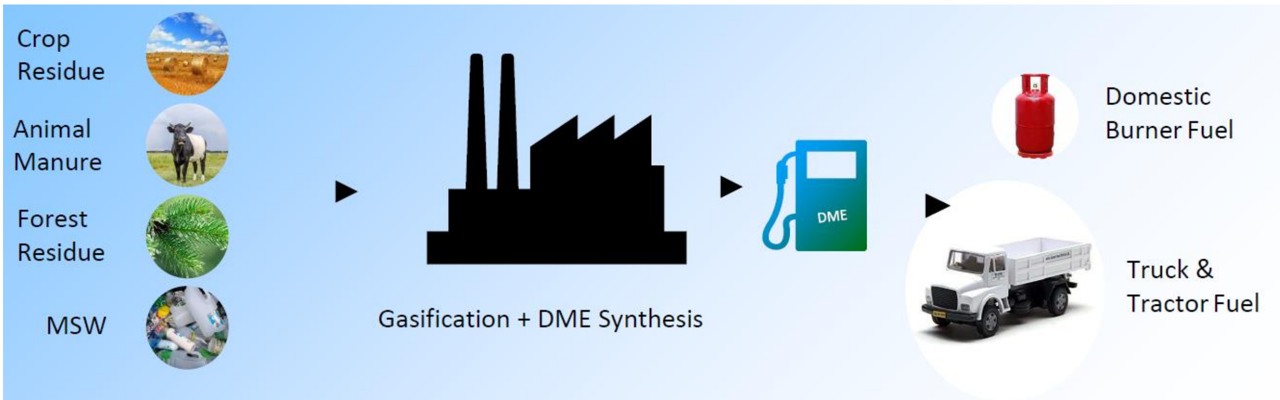
- **India**

The Indian market is interested in LPG-DME blends for household cooking gas and industries, and in DME diesel replacement application (Hindustan Times, 2019) (Indian Express, 2019).

The company Green Futures Inc is a US entity that was formed in 2020 to take advantage of the technology developed by the Indian start-up Amol Carbons Private Limited. It develops renewable DME for trucks and tractor fuel and for domestic burner fuel applications. The rDME process developed by the start-up is described in Figure 15.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Figure 15: Renewable DME process developed by Green Futures Inc (Apte, 2022)



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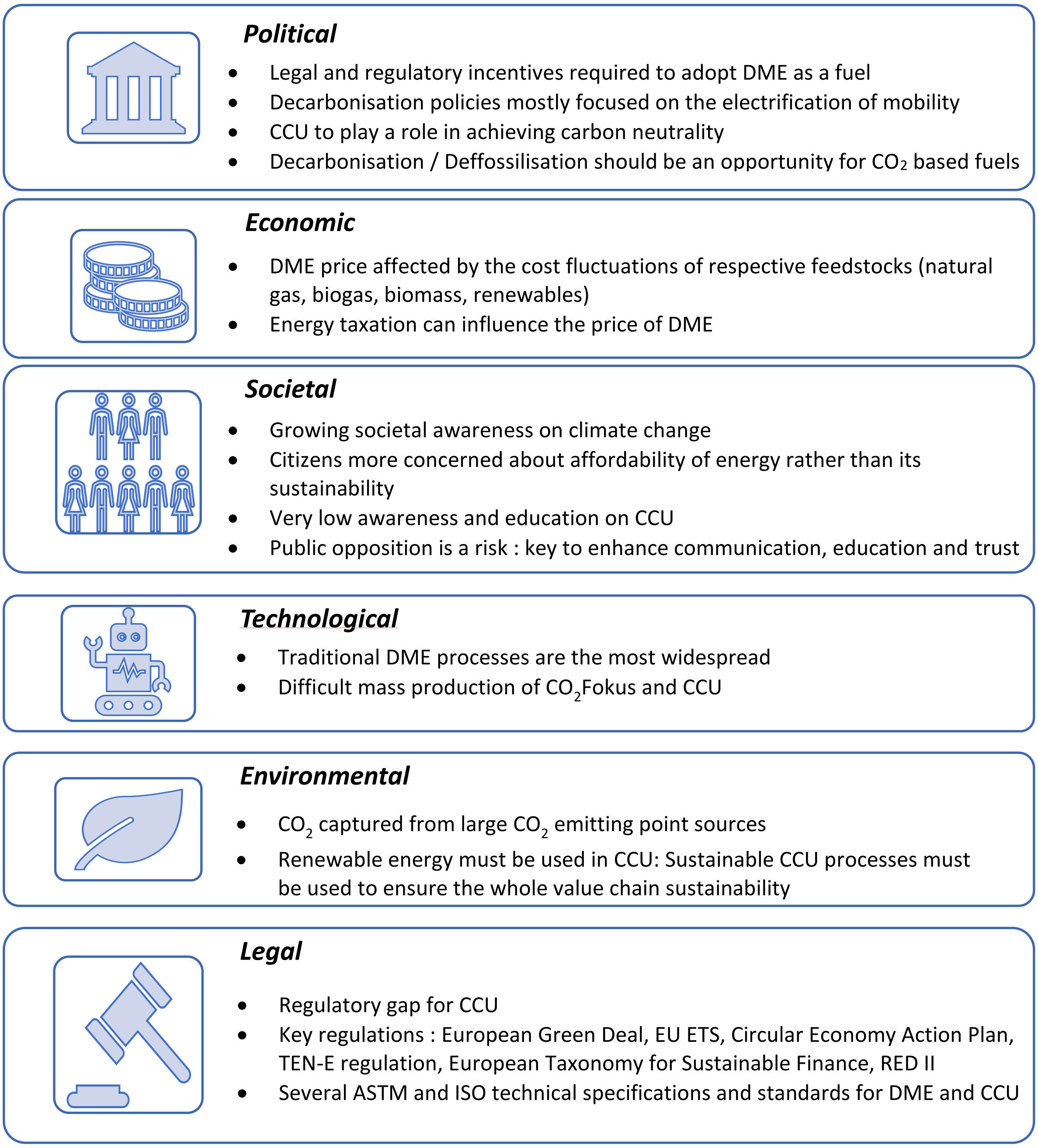
2.3 PESTEL and Regulatory analysis

The PESTEL analysis studies the Political, Economic, Social, Technological, Environmental and Legal factors influencing the CO_2Fokus technology. Key elements on the DME and CCU environment are described in this section. Figure 16 summarises the key points of the PESTEL analysis.

Figure 16 Summary of the PESTEL analysis



2.3.1 Political

Today, DME is mainly used in the aerosol and chemical industries. To extend the use of DME and rDME as an end-product (including as a fuel), political changes are required: Convincing policymakers and supporting policy changes are major steps to undertake.

To convince policy makers, one determinant argument is to connect climate concerns, current energy policies, EU objectives and policymakers' interests (e.g., reaching net zero objective, defossilisation etc.) (Anonymous Assistant professor of Social, 2020).

Relying on convincing citizens, households and corporations is not as relevant as the impact of such actions is very limited. Policy changes are more pertinent as they force society to shift habits; for instance, by forbidding the use or production of a specific product (Anonymous Assistant professor of Social, 2020). Political steps to extend the use of DME as an end-product (fuel) are tight up with regulatory changes (see legal section of the PESTEL analysis).

Political and geopolitical considerations of the economy decarbonisation

As decarbonisation could be an argument to bring CO_2Fokus - a technology capturing carbon from industrial emissions to produce DME / a renewable fuel - to the market, it was relevant to question the considerations for policymakers to choose a type of energy over another to achieve decarbonisation.

> *"At a state level for the decarbonisation, we don't need small steps for the next 30 years. We need huge steps. The question is what technologies and policy frameworks are helpful for huge steps"*
> (Gara, 2020)

According to Stefan Gara, policymakers have a systemic approach for decarbonisation, and favour considering a system of solutions for each sector rather than setting for one specific type of energy. For example, in the mobility sector, it is essential to look at energy as a service rather than as one product, and to put an emphasis on improving the efficiency of energy services. In this sector, policymakers also consider space optimisation, implying the reduction of the number of vehicles and cost effectiveness of logistics (recharging stations for vehicles) (Gara, 2020).

The electrification of mobility is strongly supported by policymakers and seems to be the preferred decarbonisation solution of light road transportation in the EU over sustainable fuels, as most climate scenarios rely on the electrification of vehicles and the switch to biofuel for maritime and air transport (Mirova, 2019). Electric vehicles however do not systematically lead to decarbonisation as it depends on the source of electricity.

Additionally, there are geopolitical considerations beyond decarbonisation. The Paris Agreement sets out a global framework to mitigate climate change effects by limiting global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. These common decarbonisation efforts entail a complete change in the industry in the next 30 years. Among policymakers and institutions, there is a strong move towards understanding and limiting the impacts of climate change. Companies are imposed to limit their CO_2 emissions, but behind decarbonisation, there are also strong geopolitical influences at stake:

- **To shift to renewables**: for example, in Russia, the shift to renewable energies is strongly influenced by geopolitical factors. The energy strategy of the country consists in maximizing the use of domestic energy sources to realise the potential of the energy sector (IEA, 2019). Due to its considerable fossil energy resources (natural gas and oil), the country has therefore an interest not to switch to renewable energy, but could exploit blue hydrogen.
- **To secure energy supply**: Natural gas pipelines between Russia and Western Europe, for instance, the Nord Stream 2 project, had a direct economic interest for some countries. However, these pipelines transported Russian gas and created energy insecurity for Europe and slowed down the energy transition. Russia's invasion of Ukraine in

February 2022 showed the urgent necessity for European nations to become independent of Russian-supplied fuels and to rethink strategically how to secure their energy supply.

The existing (fossil-based) system is very cost-intensive to change. Oil and gas companies have a direct interest in maintaining the status quo, and are facing huge challenges to adapt their business models (Gara, 2020).

CCU and the political agenda in Europe

Reuse of CO_2 is essential to achieve climate goals both in 2030 and in 2050, and CCU could be part of the solution:

> *"We don't have the luxury to see what is the most energy-efficient, economically-efficient and technologically-viable solution. There are different settings in different geographical locations. "Where one makes sense, the other doesn't, we have to keep an open mind and try to work all together to achieve our goals"* (Anonymous expert, 2020)

While CCU is not the only decarbonisation solution, experts see it as part of the mix as the ways to achieve carbon neutrality are limited. Even if it is not yet firmly established, it is recognised that CCU and CCS will play a role, even more so in the years to come (Tilling, 2020).

Political steps to use DME as a fuel

The use of DME from the CO_2Fokus technology as a fuel implies that after the CO_2 capture from industrial emissions, CO_2 is reemitted in the atmosphere. If decarbonisation using such a technology is a debate, the defossilisation of the transportation sector can be achieved with this renewable fuel. Decreasing the dependency on fossil fuels is a current debate in Europe and an opportunity for CO_2-based fuels.

Yet, today, the net zero CO_2 emission target for 2035 is a barrier to use DME as a fuel (see Legal section). However, considering that the use of e-fuels does not require replacing combustible engines (while it is the case for electric vehicles), the inclusion of e-fuels in the mix, could be part of climate mitigation and defossilisation solutions. Influencing policy makers to increase the ratio and adoption rate of renewable fuels in the transportation mix is the most important political step to introduce DME or more generally renewable fuels in this sector (Ralf Diemer T. B., 2021).

2.3.2 Economic

Capital and operating costs of CO_2Fokus

There are 2 different categories of petrochemical plants utilizing the feedstocks: direct conversion and indirect conversion.

- The case of CO_2 to DME is a direct conversion. In this type of plants, capital costs are low compared to indirect conversion plants, however the operating costs are higher.
- The reforming syngas production for instance in the usual facilities is an indirect conversion of feedstock. Capital costs in indirect conversion processes are usually higher than those of the direct plant, but the operating costs are relatively lower. DME produced in established petrochemical facilities has currently lower costs than DME to be generated from CO_2 and hydrogen in dedicated plants
- (Hamid Godini, 2020).

Hamid Godini estimates that the cost of introducing CO_2Fokus technology can split as follow:

- The main capital costs are transportation and storage. These costs could be significant especially if the location of the operation, consumption and raw material sources are not nearby. The costs may vary depending on the generation location, platform and scale of production. Also, downstream separation could be costly if a classical approach such as separate distillation and purification units was used (Hamid Godini, 2020).

- The main operating costs would come from the utilities used. There could be a cost saving from 3D printing reflected in the capital cost and controlling the operation of the reactor. However, this would probably have no significant impact on the OPEX and the savings from the 3D printing will not be a major factor in the large scale process.

Price of DME

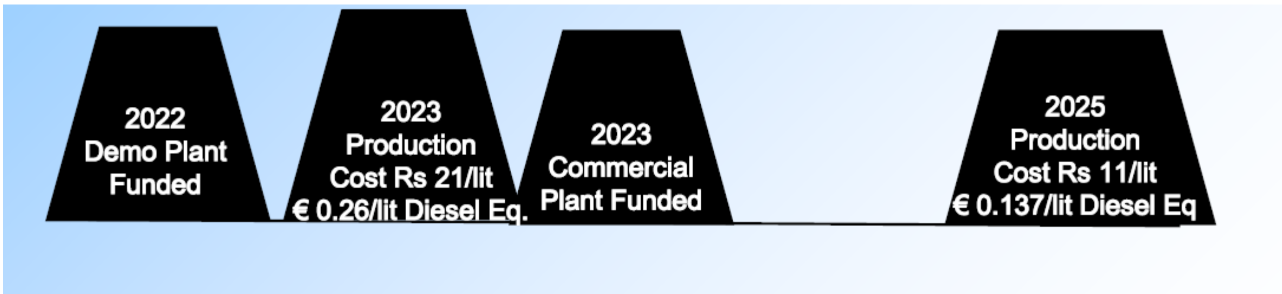
According to Hamid Godini, the main source of DME comes from natural gas feedstocks, and therefore, the price of DME might be directly or indirectly affected by cost fluctuations of natural gas (Hamid Godini, 2020).

The Japan DME Association analysed the price of DME depending on the feedstock (Ohno, 2022):

- **DME produced from biogas**: The shipment price of DME produced from biogas is lower for the larger plant scale. The domestic wholesale price of DME is lower than LPG.
- **DME produced from wood chips**: The sale price of DME produced from wood chips is greatly dependent on the price of the raw material. To be considered economical in comparison to the domestic wholesale price of LPG (100-160 yen/kg), raw materials should be obtained at 10 yen/kg or less.
- **DME produced from renewables**: The wholesale price of DME produced from electrolysis hydrogen and recovered CO_2 using renewable electricity is predominantly affected by the unit price of electricity. Equipment costs do not have significant impact, but a location with low electricity prices is advantageous in terms of cost. Compared with the domestic LPG wholesale price (100-160 yen/kg), if the unit price of electricity is 2.5 yen/kWh or less, it is considered economical.

Green Futures Inc, a DME producer in India, forecasts their DME production cost to be equivalent to EUR 0.26 per litre diesel in 2023 and EUR 0.137 per litre Diesel in 2025 (Figure 17).

Figure 17: Green Futures Inc, DME production cost in India (Apte, 2022)



Instrument to decrease DME price

Energy taxation is an economic leverage that could influence the price of DME. As of 2022, if used as a fuel, DME energy tax is the same as fossil fuels. However, to incentivise the use of DME and decrease its price to be competitive with other fuels, the promotion of a lower energy tax rate is needed. eFuel Alliance proposed in June 2022 the following targets for the Energy Taxation Directive (ETD) to allow bio and e-fuels to be competitive. Figure 18 demonstrates the major price advantage for e-fuels in terms of energy tax in comparison to gasoline and diesel, but also to other sustainable alternatives such as crop-based biofuels or sustainable biofuels.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Figure 18 Overview of different tax rates (motor fuels) expressed in euro cents per litre (Ralf Diemer e. A., 2022)

Motor Fuel	Energy tax in 2023 in ct/l	Energy tax in 2033 in ct/l
Gasoline	37.52	37.52
Diesel	40.21	40.21
Kerosine	4	39.56
Natural gas in €/GJ	7.17	10.75
Crop-based biofuel (Diesel-equiv.)	20.12	40.21
Sustainable biofuel (Diesel-equiv.)	20.12	20.12
Advanced biofuel (Diesel-equiv.)	0.56	0.56
eFuels (Diesel-equiv.)	0.56	0.56

Besides, CO_2 tax (EU emission trading system) is beneficial for CO2Fokus technology, as it captures carbon. This tax will make CO_2Fokus product much more competitive, and the competitive advantage will depend on the rate of the carbon tax (Gara, 2020) (Cf Legal section of the PESTEL and Regulatory analysis).

2.3.3 Societal

Public awareness of environmental issues

Public awareness of climate change is rising. Surveys and recent climate demonstrations have shown that the environmental awareness has increased as people are becoming more aware and supportive of climate change mitigation measures. According to the Eurobarometer Special 513, more than nine in ten Europeans (93%) believe that climate change is a serious problem, including 78% who say it is a very serious problem and 15% a fairly serious problem (European Commission, 2021).

This setting is favourable for many new technologies, and as the Covid-19 crisis has shown, people are able and willing to make changes in emergency situations (Anonymous Assistant professor of Social, 2020).

Public perceptions about energy

Citizens tend to be more concerned about the affordability of energy rather than its sustainability. Yet, in the last few years, the environmental impact and the risks associated with the way energy is produced and used have gained more importance for citizens. People are urged to adopt more sustainable habits and the source of the energy that they are using matters more than before.

Public perception of energy is often linked with geopolitical factors: country or region, political and business interests, public and local beliefs may influence it. In some countries, dependency on fossil fuels is a political and public concern, while in some other nations, this dependency is not as negatively perceived and energy transition is not entirely supported due to wide local availability of fossil resources and the reliance on existing systems (Cismaru, 2020). For instance, the Russian energy system is centralised, state-owned and based on utilisation of fossil energy, being considered as a cornerstone of national economy, security and identity. A survey led by the European Social Survey on public perceptions on climate change and energy revealed that *“Russia also has the largest proportion of respondents* *who report being sceptical that climate change is even happening - almost 18% of respondents do not believe that the world's climate is probably or definitely changing"* (European Social Survey, 2018).

While people may care if the energy that they are using is sustainable, it will not be a priority for them to switch to a more sustainable energy. For innovative technologies (fuels), people need to know that it works and that the supply is stable, but choosing a different type of fuel for their car may be a challenge and trigger hesitations. The public has however, a positive opinion on transportation becoming more sustainable (e.g., public buses shifting to natural gas) (Anonymous Assistant professor of Social, 2020).

Public acceptance and social perceptions of CCU

According to Diana-Maria Cismaru, very few people are truly aware of CCUS technologies. The majority has never heard of CCU or CCS or do not know much, because they think they do not have the technical background (Cismaru, 2020).

Studies led by Diana-Maria Cismaru showed that, while the utilisation of carbon is embraced by the public, some concerns are raised regarding carbon storage. While there is a limited risk in carbon storage, there is a tendency from the public to perceive the risk higher than the reality. The survey revealed that some people also considered some risks in the capture dimension, highlighting the misinformation of the public on the topic (Cismaru, 2020). Findings of Cismaru are confirmed by "Strategy CCUS" survey on stakeholder acceptance which revealed the overall social acceptance CCUS. The quantity of raw materials used, and the location of the facilities however highly affect the environmental and societal perception associated with the process (Fernanda Veloso, 2020).

Steps to influence the use of DME and CCU at a society level

Even with an effective technology, if society does not want or like it, the implementation can be very challenging, depending on the nature of the project and location of implementation, as well as the mechanisms put in place to effectively engage with the local stakeholders. Recently, in many countries, CCUS was blocked by public opposition, illustrating the importance of considering public acceptance (Cismaru, 2020). For example, in the Netherlands, a CCS project was unsuccessful due to local public opposition (Akerboom, 2021). The issue was mainly due to safety concerns in the region due to unsafe infrastructure, but also due to the history of how the region had been treated by the government.

It is often assumed that the following factors mainly determine people's opinions:

1. Communication and knowledge, noting that knowledge is a small part of people's opinion;
2. Trust with the organisation(s) developing the project;
3. Procedural fairness, involvement of the community and equal distribution of the costs and benefits;
4. At a local level, the meaning of a place can have an importance (personal, historical, cultural, emotional etc.). Depending on the context (e.g., transport pipeline in one's backyard, living in an industrial area), the perspective may vary.
5. Safety concerns, even when explanations are given.

Moreover, public opposition can be created due to the following reasons:

- Mistreated or ignored communities;
- Late involvement of the communities/public;
- Lack of opportunities for the public to have their voices heard or neglecting their opinions.

The steps to take to influence the use of DME and CCU at a society level recommended by social experts would be as follows:

1. Fact-based information and education on circular economy and CCU topics are important to change the perception and opinion of the public. Education is indeed a determinant element to improve acceptance in society, starting from information campaign for youth and school students. Powerful opinion leaders could also be leveraged to increase awareness of the topics. Since few people are familiar with the term “circular economy” or “CCU” education and information work are required on this topic (Anonymous Assistant professor of Social, 2020).
2. Demonstration that the innovation is tied with people' interests. According to Diana-Maria Cismaru, it is possible to create acceptance on anything, on the condition of a pro-active and smart communication: *“Between public opposition and public acceptance, the only step is communication.”* (Cismaru, 2020)
3. Dialogue with policy makers and CCU and CCS stakeholders would be more determinant than the general public. CCU and CCS stakeholders indeed have the background knowledge and relevance to understand the project. In order to spark their interest, there should be benefits for them that could derive from discussions had with them to better understand their motivations and challenges.
4. Demonstration of the competitive first-mover advantages for industries using CO_2Fokus technology.
5. Building a business case with positive outcomes to share with the broader media. However, bringing attention to the project at high level may also be risky as it may create some opposition (Anonymous Assistant professor of Social, 2020).
6. Exchanging with NGOs may be useful in order to understand their views and concerns. Many NGOs are not in favour of CCUS for the following concerns:
    a. CCUS is an argument for keeping coal plants longer;
    b. CCUS is an argument that nothing needs to be changed regarding CO_2 emissions;
    c. CCUS is considered not to be energy efficient: Separating CO_2 from waste gas stream consumes a lot of energy, therefore there needs to be more input (more fossil primary energy resources) for the same amount of output energy (Gara, 2020).

2.3.4 Technological

Technological challenges of CO_2Fokus

Traditional (grey) industrial DME production relies on methanol, coal or natural gas and is considered to be a relatively simple, large-scale and robust DME production method. Replacing the technology and industrial process would require significant valuable results from the proposed CO_2Fokus process.

An important limitation of CO_2Fokus technology is the mass production of DME that may not be possible with the designed process and proposed technology. Indeed, the 3D printed reactor and solid oxide cells face scale-up difficulties from the pilot to industrial scale and therefore a continuous production might be hard (Joost Smits, 2020).

Besides, the CCU technology is also an important technical limitation for CO_2Fokus. The flue gas streams emitted from industrial plants only contain about 15% of CO_2, leading to high energetic and investment costs (Bossanne, 2020).

Existing rDME production technologies

Among the proprietary rDME production technologies, the following are described:

- *KEW technology Ltd*

KEW Technology is a sustainable energy solutions company using proprietary technology and development capability to convert waste and biomass-based feedstocks into advanced energy vectors. They own a proprietary and proven pressurised gasification technology to optimise cost effectiveness and energy efficiency (Cocchi, 2022).

- *INDIGO technology*

The INDIGO technology – "Integrated DME Generating Operations" is developed by Fraunhofer Institute for Solar Energy Systems and was filed for patent registration in 2022. The process of this technology relies on the intensification of DME production by combining reaction and distillation into a single unit operation. While the potential of new catalysts for the promising liquid phase DME synthesis must be further explored, the technology already offers ISO conform production of pure DME as well as scalability and tunability (Ouda Salem, 2022).

- *DME market players producing DME with proprietary technologies*
  - Aerosolex produces DME with a proprietary DME technology based on catalytic distillation principle.
  - Oberon Fuels has developed proprietary skid-mounted, small-scale production units that convert methane and carbon dioxide to DME from various feedstocks, such as biogas from dairy manure and food waste.

This short benchmark of proprietary or patented technologies demonstrates the variety of current processes to produce DME or rDME. These technologies will be indirectly in competition with the CO2Fokus technology.

2.3.5 Environmental

Carbon capture utilisation and environmental sustainability

As blue hydrogen has been recognised in the current legislation as a way to transition to green hydrogen, renewable hydrogen, including green and blue hydrogen are relevant to decarbonisation. Hydrogen gained much importance in recent years, which is of importance to the CCU market.

The process to capture CO_2 can be done either from:

- Industrial emissions;
- Bio-source (i.e., biogenic CO_2) such as fermentation, bio-energy production or similar other processes;
- Direct air capture.

In the case of CO_2 industrial emissions capture, CO_2 is typically captured from fixed point sources such as power plants and factories (Metz, 2018). Point sources are large CO_2 emitters and some of these emissions, such as those from cement manufacturing are unavoidable (Heidelberg Cement Group, 2020). The primary target are the long-lasting point sources that can be used as a way to make CCU processes technically viable to deploy at industrial scale. At the beginning, CCU processes would be easier to be developed in areas of concentrated industrial activity where symbiotic relationships could be leveraged. Hubs and clusters of industrial activity would be created, enabling the development of CCU processes. Today, CCU projects are seen mostly in ports or within concentrated industrial areas with several organisations (Anonymous expert, 2020).

CO_2Fokus produces DME from industrial emissions that would have gone to the atmosphere, and which will end up in the atmosphere ultimately if used as a fuel. However, if it had to replace (at least partly) diesel, it would reduce fossil fuels dependence and if it does not reduce CO_2 emissions when the fuel is burned, it would still reduce emissions from fossil resources that would have been used to produce an equivalent fuel.

Besides, another established concern about CCU is the high energy consumption (Anonymous expert, 2020) for CO_2 capture from industrial emissions.

Generally, CO_2 reductions will not be made if renewable energy is not used as the source of electricity in the CCU process. It is essential to stick to using CCU sustainable processes and ensure that the whole of the value chain of the product (upstream, conversion, downstream) is not generating more emissions than the ones that are saved. For example, if natural gas needs to be used as a source instead of renewable electricity, it will not contribute to emissions reduction, and the CCU process would not be valuable (Anonymous expert, 2020).

CCU fuels such as DME are an opportunity to defossilise through the storage of solar energy

The major challenge when it comes to using renewable energy as a source of electricity to produce rDME lays in the variability of renewable sources (wind or solar), which can be alleviated thanks to the support of energy storage. Energy storage options are expanding and CCU fuels constitute a way of storing renewable energy and transporting it from one place to another. Due to the very steep decrease in the cost of renewable energy, both solar and wind, a rapid expansion is expected (Taylor, 2021), as illustrated in Figure 19. This would allow an accelerated development of CCU alternatives as complementary options for defossilisation (Anonymous expert, 2020).

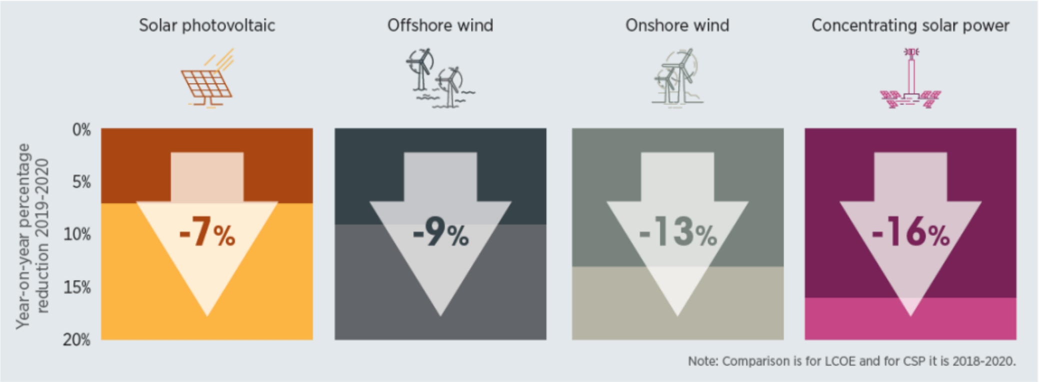


Figure 19: Global weighted-average LCOE (Levelised cost of energy) from newly commissioned, utility-scale solar and wind power technologies, 2019-2020

2.3.6 Legal

2.3.6.1 Legal barriers and opportunities to produce DME using CO_2Fokus technology

Legal experts interviewed mentioned that there is no major legal barrier for the production of DME using the CO_2Fokus technology.

"At a commercial scale, from a legal perspective, the process of converting CO_2 to DME can be set up tomorrow." The main challenges are the cost and availability around the technology rather than the regulatory barrier (Tilling, 2020).

CCU legal barriers and incentives

In the regulatory environment that aims to reduce the amount of CO_2 in the atmosphere, classic carbon capture and storage (CCS) is governed by the EU CCS regime. Under the CCS umbrella, CO_2Fokus would be excluded from the EU ETS, as CO_2 would be emitted.

As of 2022, several regulations and regulatory incentives for the decarbonisation of energy and industry co-exist, but there is a regulatory gap that needs to be addressed to cover CCU. Therefore, legislators need to be persuaded that the case of use where carbon is captured, used and reemitted should be included in the EU ETS.

Legal experts highlighted however that there is no legal barrier to use the CCU technology to capture carbon from industrial emissions and use it further in a chemical reaction. CO_2 is a waste gas and the possibility of using it as a raw material in a further line of production is an advantage from the regulatory perspective as it is aligned with its objective to minimise CO_2 emissions.

In the medium term, the capture of CO_2 from the industry will be regulated and would impact CO_2Fokus. The production of DME must be given appropriate credit as a carbon dioxide sink, and a technology to support in the context of a net-zero economy promoting CCU.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Green hydrogen legal barriers and incentives

The Seveso directive on the control of major-accident hazards involving dangerous substances could eventually be a regulatory barrier for hydrogen production as it is a highly flammable explosive gas and challenging to store. The Seveso directive imposes a threshold on the amount that can be stored: because hydrogen has such a risk of causing a major accident, the volumes that can be stored are low. As a comparison, liquid natural gas storage volumes can be higher before falling into Seveso regulation. If the CO_2Fokus process produces hydrogen without the storage required, then it would not be governed by Seveso. Yet, as discussed in the economic section of the PESTEL, regulatory incentives are needed to decrease cost of green hydrogen.

DME production legal barriers and incentives

DME stands in the category of e-fuels within the European regulatory framework and does not benefit from any support from policies in the transportation sector (Ralf Diemer, 2021). The legal framework for producing DME is however not considered a barrier (Tilling, 2020).

2.3.6.2 Legal opportunities and barriers to use DME as a fuel

Legal and regulatory incentives are required for using DME as a fuel. CO_2Fokus is about using CO_2 as a feedstock that will become a fuel, and which upon combustion, will lead to CO_2 and water emissions. If DME is used as a transport fuel, then the emitted CO_2 will not be captured. Therefore, the CO_2 captured with CO_2Fokus technology from industrial emissions is converted later for a second cycle without the possibility to be captured at the end of the tailpipe. According to Simon Tilling, the regulatory incentives to use a CO_2-based fuel are a challenge, and the way captured carbon emissions will be addressed by the regulatory regime will depend on the number of regulatory incentives from the EU (Tilling, 2020).

Beyond the carbon capture incentive for CO_2-based fuels, there is a barrier to use DME as a fuel. Indeed, the current CO_2 emission standards for new vehicles do not consider renewable fuels. As DME emits CO_2, the 0 gram 2035 target cannot be achieved. Therefore, automotive manufacturers cannot reach their target with internal combustion engines by 2035, and as this target can only be achieved with electric vehicles, with the current regulation, manufacturers would not invest in DME or more generally in e-fuels. In Europe, the eFuel Alliance advocates to expand the regulation and consider renewable fuels (Ralf Diemer T. B., 2021).

Current Green Deal changes are a unique opportunity to change the framework and get more incentives for synthetic fuels. According to Ralf Diemer and Tobias Block, to increase investments in renewable fuels, the current target of 2.6% in 2035 for renewable fuels and non-biological origins, should be raised to 5%. In such a scenario, DME and other renewable fuels could have a chance to be introduced as a fuel in the automotive market.

2.3.6.3 Regulatory frameworks impacting CO_2Fokus

Table 4 presents a synthesis of regulatory frameworks impacting CO_2Fokus technology or the use of DME as a fuel.

Table 4: EU regulations impacting the CO2Fokus technology

Regulatory frameworks	Regulation summary and impact on CO_2Fokus
European Green Deal	The European Green Deal proposes a new EU climate-neutrality commitment for 2050 and an increased EU 2030 emission reduction target of at least 50% by 2030 (up from 40%). Regulations are open and could have an impact on the use of DME as a renewable fuel.

CO_2 emissions standards for cars, vans and trucks	There is a need of a crediting system of renewable fuels in the CO_2 standards for cars, vans and trucks From 2025, a super-credits incentive mechanism for zero- and low-emission vehicles (ZLEV) crediting system will be introduced both for car and van manufacturers, allowing the relaxation of manufacturers' specific emission target, if its share of new ZLEVs (vehicles with emissions between 0 and 50 g CO_2/km (WLTP)) registered in a given year exceeds the following benchmarks: - Cars: 15% ZLEV from 2025 on and 35% ZLEV from 2030 on - Vans: 15% ZLEV from 2025 on and 30% ZLEV from 2030 on **(European Commission, 2021)**.
Energy Taxation Directive	The Energy Taxation Directive is the EU framework for the taxation of energy products including electricity, motor and most heating fuels. It sets minimum rates of excise duty in the objective of encouraging a low-carbon and energy efficient economy and sets out structural rules to avoid potential distortions of competition across the EU **(KPMG, 2022)**. The current framework is from 2003 and does not differentiate between fossil and renewable fuels.
Circular Economy Action Plan	In 2015, the European Commission presented the Circular Economy Action Plan, which includes measures that will help stimulate Europe's transition towards a circular economy while boosting global competitiveness, fostering sustainable economic growth and generating new jobs. It aims at implementing actions along the whole cycle, from production and consumption to waste management and the market for secondary raw materials. In 2018, the EC adopted a monitoring framework for the circular economy, allowing policy makers to identify good practices and prioritise areas requiring further action. In its resolution of July 2015 on 'resource efficiency and circular economy', the European Parliament requested the Commission to review the Ecodesign Directive to broaden its scope beyond energy-related products and include resource-efficiency criteria related to reparability, durability, upgradability and recyclability of products. However, such revision of the Directive has not been implemented yet. Despite the legislation on air pollution, the concentrations of certain air pollutants are above EU air quality standards in most EEA countries; the situation is especially severe in urban areas. The plan announced a robust carbon removal certification mechanism: - To allow tracking of the CO_2 fluxes, especially for CCU technologies that are not yet commercially mature; - To allow regulatory incentives for market uptake of CCU products, which may be slow in the short term due to high investment costs.
TEN-E regulation	CO_2 infrastructure projects call for European legislators to extend the scope of existing legislation – such as the TEN-E regulation and EU ETS directive – to prepare for the rollout of CO_2 and clean hydrogen infrastructure.
Emissions Trading Scheme (ETS) Directive	The EU ETS is a mechanism that could underpin the commercial viability of new CCS and CCU technologies but in its current form does not allow the full realisation of their potential. In the context of CCU, the ETS does not reward the capture and use of CO_2 in materials, for example building and construction materials. A suggested 2022 revision however acknowledges CCU chemically and permanently bound in a product and recognises the need to avoid double counting of CO_2 released from CO_2-based products. The EU ETS is now in its third phase. It covers around 45% of the EU's GHG emissions from more than 11,000 power stations & industrial plants as well as airlines operating between the EEA countries. The legislative framework of the EU ETS for the 2021-2030 period (phase 4) was revised in early 2018 to enable it to achieve a 43% reduction in ETS

	emissions by 2030 compared to 2005 levels. The revision increased the pace of annual reductions in allowances to 2.2% as of 2021, instead of 1.74%. The system of free allocation of allowances will be prolonged for another decade and has been revised to focus on industrial sectors at the highest risk of relocating their production outside of the EU, where carbon pricing is not put into effect. As indicated in the European Taxonomy for Sustainable Finance (Taxonomy), all modes of CO_2 transportation to permanent geological storage – pipeline, ship, barge, train, truck – are allowed. CCU is excluded from European Taxonomy for Sustainable Finance. Its inclusion could incentivise the use of CO_2Fokus technology to capture carbon and produce DME.
Carbon tax	Carbon tax measures intend to reduce CO2 emissions. Carbon taxes have been introduced to some extent in countries like Sweden, Denmark or Finland, providing an incentive for economic actors to reduce their greenhouse gas emissions.
Renewable Energy Directive (RED) II	The original Renewable Energy Directive (2009/28/EC) (RED I) mandated 20% of renewables in the EU by 2020, along with a 10% renewables target in transport. The Renewable Energy Directive (2018/2001/EU) (RED II), revises the 2009 text and sets the binding target of 32% share of renewables in the EU energy mix by 2030 with a clause that allows for a possible revision by 2023. EU members also must ensure that at least 14% of their transport fuels come from renewable sources by 2030 . In RED II, biofuels and bioliquids are recognised as instrumental in helping EU countries meet their 14% renewables target in transport. This directive enables - The diversification of energy, - Biofuels - Advanced biofuels To be more supportive, the announced revision of RED II should consider industrial realities as far as the conditions for renewability, additionality, and temporal and geographical correlation of electricity use in CCU.

2.3.7 Regulatory standards

While it is too early to make a statement about the CO_2Fokus technology complying with specific standards, several standards that are relevant to the technology were identified. The CO_2Fokus technology as a whole but also some parts of the process, will have to comply with standards when it reaches higher TRLs and/or full industrial scale. ASTM International and ISO have also developed technical specifications for fuel-grade DME (Table 5) (International Organization for Standardization, 2022).

Table 5 DME standards relevant for the CO2Fokus technology

Standards	Description
ISO 16861:2015 Petroleum products — Fuels (class F) — Specifications of dimethyl ether (DME)	Specifies the characteristics of DME used as fuel of which the main component is the dimethyl ether synthesized from any organic raw materials. DME used to manufacture the LPG-DME blend(s) will comply with either ISO 16861 or ASTM D7901-20.

ISO 17196:2014 Dimethyl ether (DME) for fuels — Determination of impurities — Gas chromatographic method	Specifies a testing procedure for methanol, CO, CO_2, methyl formate, ethyl methyl ether, and hydrocarbons up to C_4, in DME used as fuel by the gas chromatography method.
ISO 17197:2014 Dimethyl ether (DME) for fuels — Determination of water content — Karl Fischer titration method	Specifies a testing procedure for the amount of water content in DME used as fuel by the Karl Fischer titration method.
ISO 17198:2014 Dimethyl ether (DME) for fuels — Determination of total sulphur, ultraviolet fluorescence method	Specifies a testing procedure for the sulphur content in dimethyl ether (DME) used as fuel by the ultraviolet (UV) fluorescence method.
ISO 17786:2015 Dimethyl ether (DME) for fuels — Determination of high temperature (105°C) evaporation residues — Mass analysis method	Specifies a testing procedure for high temperature (105 °C) evaporation residue in DME used as fuel by the mass analysis method.
ISO 22760-1:2019 Road vehicles — Dimethyl Ether (DME) fuel system components — Part 1: General requirements and definitions	Specifies general requirements and definitions of Dimethyl Ether (DME) fuel system components, intended for use on the types of motor vehicles defined in ISO 3833.
ISO 22760-2:2019 Road vehicles — Dimethyl Ether (DME) fuel system components — Part 2: Performance and general test methods	Specifies performance and general test methods for Dimethyl Ether (DME) fuel system components intended for use on the types of motor vehicles defined in ISO 3833.
TTS 59 – DME and LPG blend	LPG used to manufacture the DME/LPG blend(s) must comply with the requirements for Propane/Butane mixture specified in TTS 59 (Local specification for LPG).
ISO 16384: 2012	Refrigerated hydrocarbon and non-petroleum based liquefied gaseous fuels – DME measurement and calculation on board ships.
ISO 16381: 2015	Petroleum products – Fuels (class F) – Specifications of DME.
ISO 29945:2016	Refrigerated non-petroleum-based liquefied gaseous fuels – DME – Method of manual sampling onshore terminals.

ISO also developed a working group ISO/TC22/SC41/WG8 which is focusing on developing standards for DME fuel systems (refuelling connector etc.) (Klaus Lucka, 2022).

Table 6 describes the chemical requirements to blend DME and LPG.

Table 6 Chemical requirements for DME/LPG blends (Randhir Ramjattan, 2022)

Parameters	Limit for DME/LPG blend(s)	Test method(s)
Mass fraction of DME in gaseous phase of DME/LPG blend(s)	<20 % mass	ASTM D2163
Vapor pressure at 40°C	<1380 kPA	ASTM D1267
Ethyl mercaptan (odorant)	>25 mg/m^3	ASTM D5305 or GPA 2199
Evaporation residues	<0.05 mL	ASTM D2158
Total sulphur	<140a mg/kg	ASTM D6667
Corrosion (cooper strip)	Maximum corrosion index: 1	ASTM D1838 or ISO 6251
Free water	None	EN 15469 or Visual inspection

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Table 7 lists the standards related to carbon capture and Table 8 lists the standards related to nanotechnologies.

Table 7: Carbon capture standards relevant for the CO_2Fokus technology

Standards	Description
ISO/TR 27912:2016 Carbon dioxide capture — Carbon dioxide capture systems, technologies and processes	Describes the principles and information necessary to clarify the CO_2 capture system and provide stakeholders with the guidance and knowledge necessary for the development of a series of standards for CO_2 capture.
ISO 27913:2016 Pipeline transportation systems	Specifies additional requirements and recommendations not covered in existing pipeline standards for the transportation of CO_2 streams from the capture site to the storage facility where it is primarily stored in a geological formation or used for other purposes (e.g., for EOR or CO_2 use).
ISO/TR 27915:2017 Quantification and verification	Presents a review of publicly available literature identifying materially relevant issues and "good practices" for quantifying and verifying GHG emissions and reductions at the project level. Its scope covers all components of the CCS chain and includes a lifecycle assessment approach to estimating project level emissions and emission reductions from project assessment, construction and operations.
ISO 27917:2017 Vocabulary – cross cutting terms	Defines a list of cross-cutting terms commonly used in the field of carbon dioxide capture, transportation and geological sub-surface storage including through storage in association with enhanced oil recovery (EOR) operations.
ISO/TR 27918:2018 Lifecycle risk management for integrated CCS projects	Designed to be an information resource for the potential future development of a standard for overall risk management for CCS projects.
ISO/TR 27921:2020 Cross Cutting Issues – CO_2 stream composition	Describes the main compositional characteristics of the CO_2 stream downstream of the capture unit, taking into account common purification options.

Table 8: Nanotechnology standards relevant for the CO_2Fokus technology

Standards	Description
ISO TC 229 Nanotechnologies	Standardisation in the field of nanotechnologies that includes either or both of the following: 1. Understanding and control of matter and processes at the nanoscale, typically, but not exclusively, below 100 nanometres in one or more dimensions where the onset of size-dependent phenomena usually enables novel applications, 2. Utilising the properties of nanoscale materials that differ from the properties of individual atoms, molecules, and bulk matter, to create improved materials, devices, and systems that exploit these new properties.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

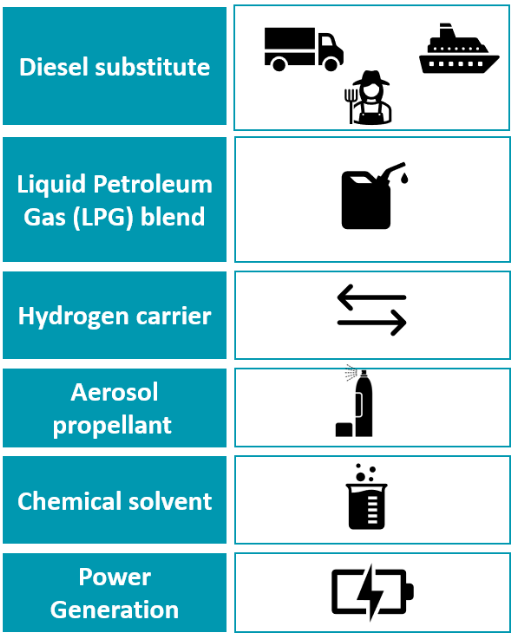
3 DME industry analysis

This section explores the different uses of DME today and future opportunities.

3.1 Market opportunities delimitation and characterisation, and demand analysis

The global DME market is divided into six main segments, as illustrated in Figure 20.

Figure 20 DME market segments



While aerosol, chemical solvent and LPG blends are the main global applications, interest in new markets has emerged over the past few years with global players investing in their exploration and development. The refrigerant market has a high potential, with power generation the least developed.

3.1.1 Segment 1: DME as a fuel, diesel replacement for transportation (trucks, shipping) and machines (in agriculture)

In 2017, transportation accounted for 27% of total greenhouse gas emissions in the EU-28, representing one of the fastest growing greenhouse gas sources since 1990 (European Environment Agency, 2020). As the European Commission set the goal of reaching a 90% reduction in transport-related greenhouse gas emissions by 2050 to achieve carbon neutrality in Europe, ambitious changes are expected in the transport sector.

DME has the potential to replace diesel in the transportation sector and in machines. Its clean properties make it an ideal fuel for defossilisation and decarbonisation (even though it emits CO_2 when burned as fuel). DME can either be blended with diesel or fully replace diesel in vehicles or machines. DME and diesel blend is a first step for the introduction of DME as a fuel, as it can enable a gradual market introduction for DME (Klaus Lucka, 2022). The following section explores the diesel replacement segment.

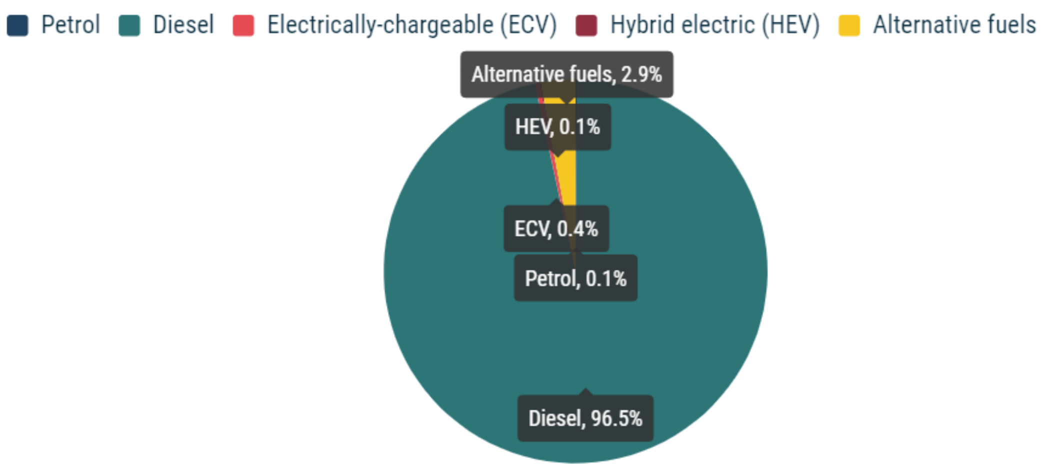
3.1.1.1 Trucks, a niche market for DME as a transportation fuel

3.1.1.1.1 Why DME as a fuel for trucks?

In the EU-28, in 2020, heavy duty vehicles (HDVs) were responsible for 27% of road transport carbon dioxide (CO_2) emissions and almost 5% of total EU-28 GHG emissions. Since 1990, these emissions have increased by 25% and in the absence of new policies, they are projected to further increase (European Environment Agency, 2020). In 2020, diesel dominated the truck fuel market share, representing 96.5% of EU truck registrations (Figure 21).

As several challenges have been raised for the commercialisation of electric vehicles and fuel cell vehicles, DME can be a **complementary solution to contribute to defossilisation** (Ock Taeck Lim, 2022).

Figure 21: New truck registrations by fuel type in the EU (ACEA, 2020)



"DME is perhaps the ideal fuel people are not aware of." (Munson, Vice President Oberon Fuels, 2021) (Munson, Vice President Oberon Fuels, 2021)

"Diesel is difficult to beat: it's cheap, it's available everywhere, and its full of energy. But if you can't use diesel anymore because of the emissions, DME provides a simple, compelling and available replacement." (Kidder, 2021)

"Renewable DME can be used in internal combustion engines on the road, and provide a long-term defossilisation alternative for transport sector segments where electrification is challenging" (SHV Energy, International DME Association, 2020).

DME has the potential to replace diesel in heavy duty vehicles, due its multiple properties that make it attractive in this segment:

- DME has a **very high cetane number** guaranteeing the fuel's ignitibility in compression ignition engines.
- DME has **excellent combustion properties** making it an ideal fuel for current diesel engines (Volvo, 2012) (Ock Taeck Lim, 2022).
- DME is a **clean alternative fuel** that can contribute to defossilisation and decarbonisation and respond to the strengthening air pollution regulations (Ock Taeck Lim, 2022). A 20% DME blend in diesel reduces soot by 50%. DME CO_2 emissions are also 20% lower than gasoline (Fleisch, 2022).
- rDME can be used as a replacement for diesel in engines, requiring only an **inexpensive retrofit of the vehicle** (SHV Energy, International DME Association, 2020) (Fleisch, 2022).
- In terms of **safety and driveability**, it is a low-pressure liquid fuel (10 bar) that is deemed to be customer friendly with quiet operations and no cold start issues (Fleisch, 2022).

These determinant points are developed in the following section.

3.1.1.1.2 DME trucks pilot projects overview

3.1.1.1.2.1 List of DME trucks pilot projects

Numerous companies performed demonstrations and pilot testing of heavy-duty vehicles powered by DME in the last decade. Table 9 describes these projects and their outcomes.

Table 9: DME heavy duty vehicles pilots projects

Organisation	Description of the DME truck project
Oberon Fuels	Oberon Fuels has been working on the development of DME for more than a decade, producing DME from waste and/or renewable resources. In 2013, the company built its first pilot plant in Brawley, California, producing the first fuel-grade DME in North America. It has since been developing modular, small-scale production units which can produce up to 10,000 gallons of DME a day. The company has been involved in several global vehicle demonstrations led by Volvo Trucks, Mack Trucks, and Ford Motor Company, providing fuel-grade DME from its plant in California **(Oberon Fuels, n.d.).**
Volvo Trucks	In August 2007, Volvo Group unveiled a demo truck from Volvo Trucks running on DME. The DME truck used a regular D13 diesel engine which, after modification of the tank system, injection system and engine management, functioned perfectly together with the DME fuel. *"Behind the wheel, it's business as usual. Performance and driving properties are just as good as in the diesel variant. The difference – and the major benefit of DME – is to be found in the low CO_2 emissions."* Mats Franzén, Engine Manager, at Volvo Trucks In 2010, Volvo led a field test of 14 BioDME trucks, fuelled by DME produced by Chemrec at the world's first BioDME plant in Piteå, Sweden. These trucks were used in fleet operations by customers throughout Sweden. The project also included the building of 4 fuel stations by the company Preem so that the trucks could be used in regular regional and local operations. **(Volvo, 2012)** Volvo's DME driveline didn't go further for several reasons, mainly because the company prioritised the development of two other drivelines, which included electric vehicles and fuel cell vehicles. This decision was partly based on the trend in policies that was in favour of electrification **(Martensson, 2021).**
Mack Trucks	In collaboration with the New York City Dept. of Sanitation (DSNY) and Oberon Fuels, Mack trucks began a demonstration in 2017 to test the performance of a DME-powered Mack Pinnacle model. The customer evaluation took place at the Fresh Kills Landfill on Staten Island, New York. The goal of the demonstration was to gather data on the use of DME fuel and vehicles in urban, heavy-load fleets **(Oberon Fuels, 2017).**
Ford Motor Company	In addition to DME applications for medium-duty vehicles such as pickup trucks in the US and Canada, Ford Motor Company investigated the use of DME in passenger cars **(Willems, 2021).** In 2015, Ford Motor Company led a 3-year project co-funded by the German government to develop the world's first DME-powered passenger car for on-road testing. The demonstration was based on the company's Ford Mondeo passenger car, modified to run on DME **(Ford Motor Company, 2015).**

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Bio Friends Inc.	Established in 2016, Bio Friends is specialised in the production and supply of clean DME, intended to be used for several applications, particularly in the aerosol and chemical compound industries. The company also explores the opportunity to use DME as an alternative fuel for diesel vehicles. A national pilot project, led by Bio Friends, was carried out in South Korea demonstrating a diesel truck fuelled by DME, where the engine modification and assembly was done by the company. In addition, Bio Friends is currently building two DME-powered pick-up trucks to be exported and demonstrated by a company in Turkey **(Cho, CEO Bio Friends, 2021).**
Iveco & FPT Industrial	A DME truck pilot was conducted by Iveco and FPT Industrial in 2022 **(Daniel Klein, 2022)**.
Ecomotive Solutions	Ecomotive Solutions, an Italian company active in the production and distribution of components and systems for sustainable mobility, has successfully completed an experiment to test DME to power an Iveco Eurocargo vehicle **(Powertrain Diesel, 2022)**.

> "*In the last two decades, DME as a fuel has awakened the interest of some DME producers to extend their range of DME usage, originally solely focused on aerosol and/or chemical solvent. For instance, some DME producers (e.g., Nouryon) are becoming more interested in reaching out to potential end users (e.g. powertrain companies and others), and discuss the potential of using DME as engine fuel*" (Kidder, 2021).

Further research is yet needed on performance evaluation and actual road driving evaluation of vehicles using DME as fuel and performed flow verification experiment of high-pressure fuel injection pump manufactured for DME (Ock Taeck Lim, 2022).

3.1.1.1.2.2 Focus on three DME trucks partnerships

Ford DME vehicle project

> "*Ford and a few other companies are picking this up (DME trucks) where Volvo left off and I think this will continue to be of great interest to some of the large heavy duty and medium duty Diesel engine manufacturers*" (Kidder, 2021).

In 2019, the research project "BMWI-C3-Mobility consortium – CO_2 neutral fuels based on methanol" was launched, involving Ford and other stakeholders, with the ambition of developing and demonstrating new ways into the CO_2-free mobility of the future using synthetic fuels based on methanol.

The following stakeholders, also illustrated in Figure 22, formed a partnership to conduct a DME vehicle pilot:

- Fraunhofer Institute for Solar Energy Systems (Germany) for the simulation CatVap (catalytic evaporation)-Exhaust;
- DENSO, a Japanese global automotive component manufacturer for the injection system;
- Grillo-Werke (Germany), a DME producer also involved in the interface fuel delivery;
- SHV Energy (Netherlands), Primagas (Netherlands) and FEV (Germany), providing the DME-filling station;
- TME RWTH Aachen, the center for mobile propulsion of the RWTH Aachen University (Germany), involved in the single-cylinder, combustion system and CatVap investigation;
- Ford (USA/Germany), for the development of the combustion system, the multi-cylinder testing and the vehicle integration and testing for light/heavy duty and marine applications.

Figure 22: Stakeholders involved in the Ford C4 Work Package lead for the DME pilot (Werner Willems, 2022)

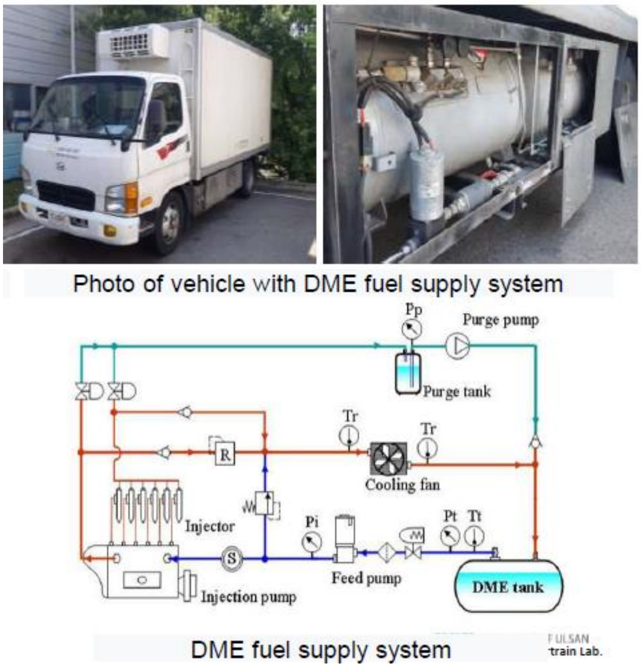
The project funded by the German Ministry of Economy is looking at methanol-based fuels including DME for light, heavy duty and marine applications.

The DME vehicles were tested in real life conditions as diesel fuel replacement on a passenger vehicle (Ford Mondeo) and a light commercial vehicle (Ford Transit Custom). According to the preliminary results of this project, the use of methanol derivatives (including DME) have been identified as an important renewable energy carrier that could contribute to defossilisation within the transport, chemical and energy sector (Werner Willems, 2022).

Bio Friends and Smart Powertrain Lab truck pilot in Korea

Tests were conducted in recent years in South Korea with medium duty trucks that ran 40,000 km in order to measure the durability and driving performance of the DME-fuelled engine and fuel supply system (Figure 23).

Figure 23: Bio Friends DME fuel supply system picture and outline (Ock Taeck Lim, 2022)



The following statements were concluded from this test:

- In terms of energy efficiency, the power performance assessment of the DME vehicle was lower than diesel's, despite the difference being small. This gap could be addressed through fuel additives to improve the performance of the fuel injection pump, and to increase the flow rate of injected fuel.
- In terms of driveability, the durability of the DME fuel supply system was proven, and there was no difficulty in driving on the road. The maximum speed of the vehicle was 110 km/h.
- As issues can arise due to increasing temperature, a technology should be developed to improve the performance of the cooling system as well as startability (Ock Taeck Lim, 2022).

Partnership Iveco Group and FPT Industrial

Iveco Group and FPT Industrial set up a truck engine running with DME. The engine had been used within a previous project involving combustion optimisation with diesel fuel to reach high brake thermal efficiency and then rebuilt for the DME project (Figure 24).

Figure 24: DME Heavy-Duty diesel base engine set-up (Daniel Klein, 2022)

The results of this project demonstrated that DME was a "sustainable diesel" fuel, and a promising solution for fleet operation, with a potential for retrofit of the existing fleet (Daniel Klein, 2022).

3.1.1.1.3 Opportunities and barriers to use DME as a fuel for HDVs

DME as a fuel for HDVs presents several opportunities and barriers that were identified and analysed.

According to Oberon fuels, the major requirements to demonstrate the performance of a fuel are the transportability, storability, resilience, energy density, GHG avoidance and supply (Munson, Vice President Oberon Fuels, 2021). Based on a 2015 Volvo Trucks study, the six following criteria are used in the subsequent sections to compare DME with other fuels or power sources:

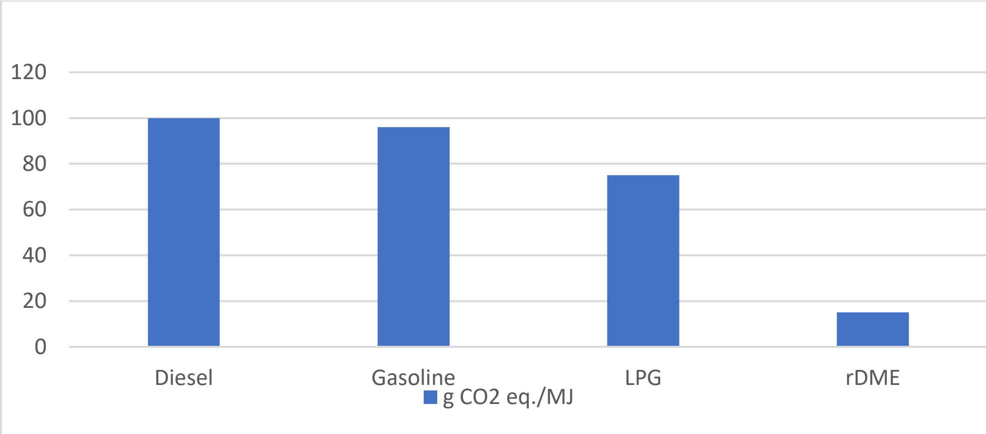
- Climate impact;
- Energy efficiency;
- Fuel potential;
- Vehicle adaptation;
- Fuel cost; and
- Fuel infrastructures.

3.1.1.1.3.1 Climate impact

DME is a clean fuel that can contribute to defossilisation and decarbonisation. Using DME as an alternative to diesel can eliminate particulate emissions and potentially eliminate the need for costly diesel particulate filters (US Department of Energy, 2021). The combustion process of DME contributes less to GHG emissions and its use significantly reduces SOx, NOx and soot emissions compared to diesel (SHV Energy, International DME Association, 2020) (Volvo, 2012) (Munson, Vice President Oberon Fuels, 2021).

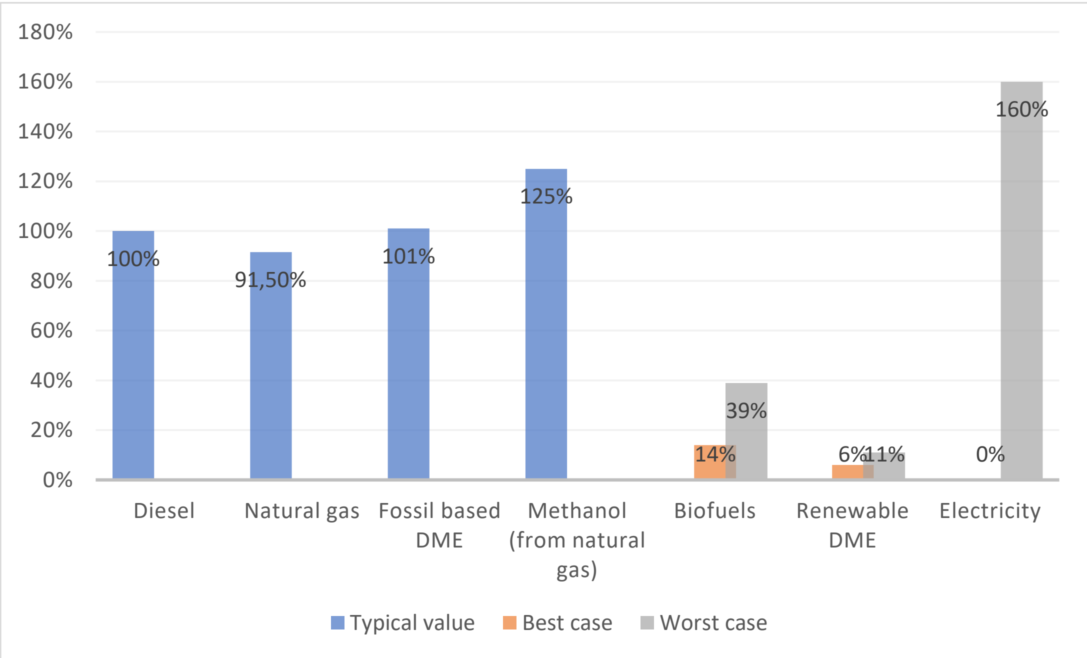
Produced from biomass, BioDME offers high energy efficiency and produces low levels of greenhouse emissions in the entire process of energy flow (Volvo, 2012). Renewable DME could provide a solution for transport sector defossilisation: it can reduce GHG emissions by up to 85% compared to diesel and heating oil, and its use significantly improves air quality (SHV Energy, International DME Association, 2020). Moreover, rDME is increasingly available and can be produced from multiple renewable feedstocks including waste streams and residues, with a low GHG footprint (SHV Energy, International DME Association, 2020). Figure 25 illustrates the significantly lower environmental impact of rDME compared to diesel, gasoline and LPG.

Figure 25: Grams of CO_2 produced per MegaJoules (SHV Energy, International DME Association, 2020)



According to the Volvo study**, renewable DME is among the most attractive fuels for climate impact**, along with synthetic diesel (from biomass) and methanol (from biomass) (Volvo, 2015). In Figure 26, the climate impact of fuels is based on the reduction/increase of CO_2 emissions compared with conventional diesel fuel. It shows that rDME allows 6% to 11% emissions reduction for HDV compared to diesel.

Figure 26: CO_2 emissions reduction/increase of fuels for HDVs compared to diesel, Volvo Trucks 2015[3]

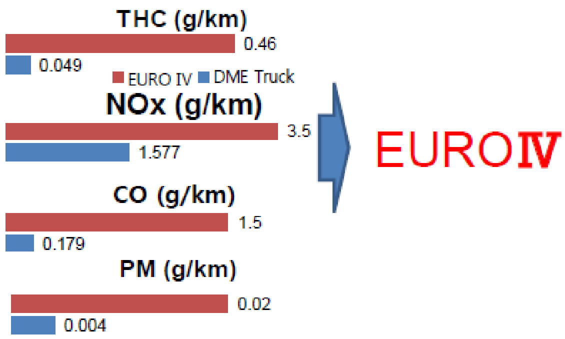


The low emission characteristics of DME used as fuel was confirmed by the latest test conducted by Bio Friends and Smart Powertrain Lab who measured emissions of vehicle engines (trucks) using DME as a fuel. Figure 27 demonstrates

[3] *Typical value is EU mix. The variation between best and worst case for the renewable fuels depends on which feed - stock they are produced from. For example, the best case for DME, Synthetic Diesel and Methanol is black liquor while the worst case is wood. The best case for electricity is wind, solar and water and the worst case is coal (Volvo, 2015).*

that the emission values of total hydrocarbon content, carbon monoxide, particulate matter and NOx emitted satisfy EURO IV[4] (Ock Taeck Lim, 2022).

Figure 27: DME vehicle emissions (Ock Taeck Lim, 2022)

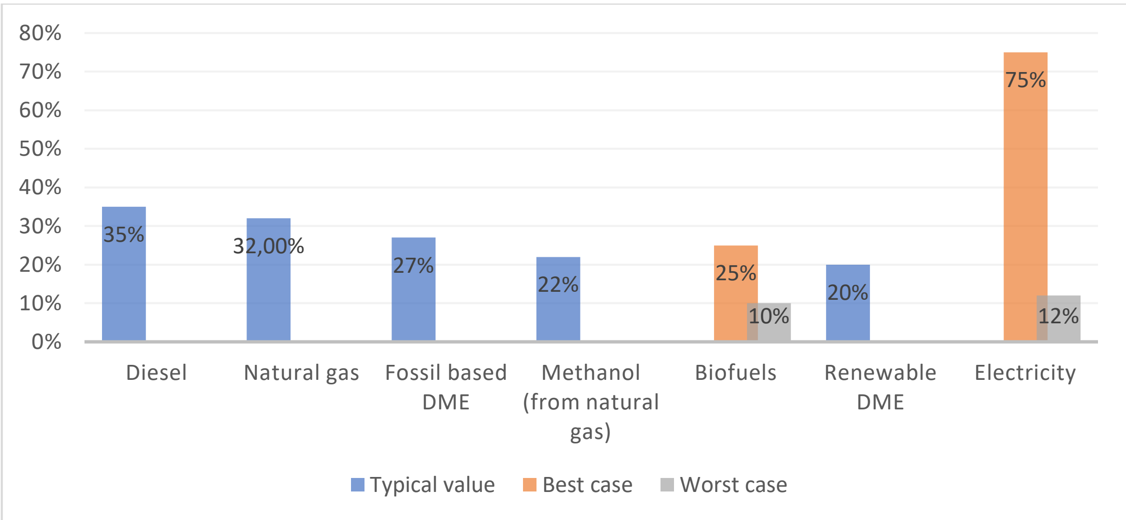


3.1.1.1.3.2 Energy efficiency

Energy efficiency is a crucial factor for commercial vehicles in general, as it implies optimised costs for the trucks. DME however has half the energy density of diesel fuel (approximately 55 %), requiring the installation of fuel tanks twice as large as that needed for diesel (US Department of Energy) (Volvo, 2012).

DME does not stand out as one of the most energy efficient fuels. Renewable DME is nearly half as efficient as diesel and natural gas in terms of energy. This factor is expressed as a percentage indicating the proportion of energy reaching the vehicle's driven wheels (Volvo, 2015). Figure 28 shows that rDME is less energy efficient that diesel or natural as gas.

Figure 28: Energy efficiency of alternative fuels in terms of proportion of energy reaching the vehicle's driven wheels (Volvo, 2015)[5]



[4] *Euro 4 emissions were introduced on all new cars from January 2005 and all newly registered cars from January 2006. To pass Euro 4 standards, petrol cars had to produce CO of no more than 1.0g/km, Total Hydro Carbon (THCs) emissions of no more than 0.10g/km and NOx emissions of 0.08g/km (Hall, 2022).*

[5] *Typical value is EU mix. The variation between best and worst case for the renewable fuels depends on which feed - stock they are produced from. For example, the best case for DME, Synthetic Diesel and Methanol is black liquor while the worst case is wood. The best case for electricity is wind, solar and water and the worst case is coal (Volvo, 2015).*

For Werner Willems, some power loss must be expected with DME, compared to diesel (Willems, 2021). According to Ivan Kisurin, DME is not interesting for fuel users because of its high consumption rate compared to diesel (Kisurin, CEO Aerosolex, 2021).

The DME vehicle test that was conducted by Bio Friends and Smart Powertrain Lab in South Korea with medium duty trucks also showed that DME fuel was less efficient than diesel (Table 10).

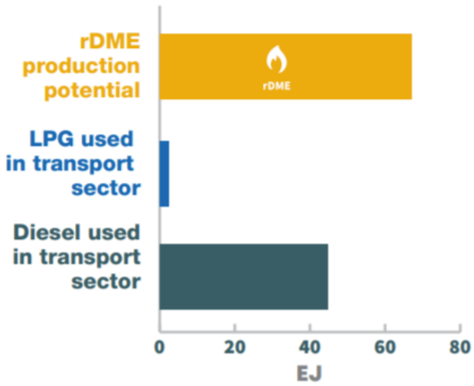
Table 10: DME vehicle fuel efficiency measurement result (Ock Taeck Lim, 2022)

	Heating value	Fuel efficiency
Diesel	35,484 MJ/m3	10.1 km/L
DME	19,210 MJ/m3	5.699 km/L

3.1.1.1.3.3 Fuel potential

In 2020, as seen in Figure 29, the global rDME production potential exceeds existing diesel and LPG use in road transport (SHV Energy, International DME Association, 2020).

Figure 29: Production potential of DME compared to LPG and diesel used in transport sector in exajoules (EJ)(SHV Energy, IDA)

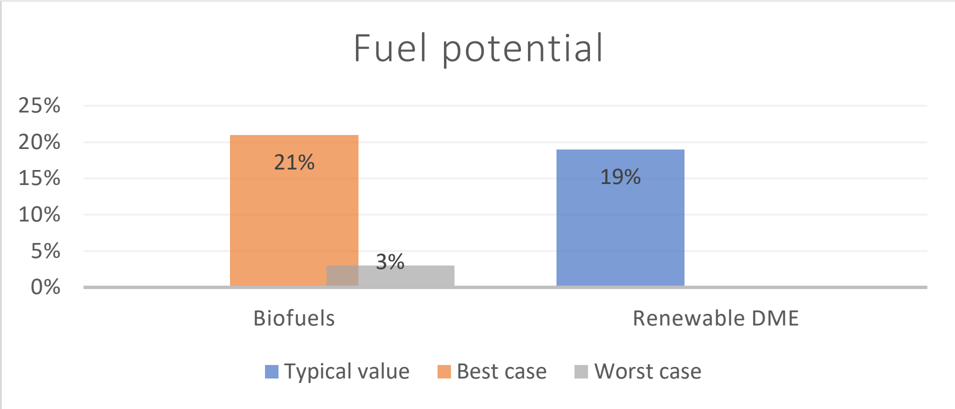


Additionally, according to a 2012 study from Volvo Trucks, by 2030, BioDME has the potential to replace more than 50 % of today's diesel usage in heavy road transport in the EU (Volvo, 2012).

DME is **produced at commercial scale today**. Today, around 10 Mtonnes a year of fossil DME can be produced via methanol. It is produced in large commercial plants with an annual output of 10 to 450 ktonnes. Renewable DME can be produced today by switching feedstock from fossil methanol to renewable methanol. As there are several sources of sustainable feedstocks for renewable DME (e.g.: waste and residues using gasification and catalytic synthesis, recovered CO_2 and renewable power), it significantly expands the resource potential to produce renewable DME. These new technologies to produce renewable DME are currently in development and in the process of scale-up. They could facilitate small-scale production, unlocking a greater resource and enabling local circular economy value chains (SHV Energy, International DME Association, 2020).

However, according to Volvo Trucks 2012 study, **none of the fuels including DME will be sufficient to replace fossil fuels** (Volvo, 2015). Figure 30 shows that rDME alone could only cover 19% of the total energy demand for transport in Europe (4,500 TWh by 2030).

Figure 30: Fuel potential in terms of % of the total energy demand for transport in Europe that can be covered by each alternative (Volvo, 2015)[6]



3.1.1.1.3.4 Vehicle adaptation

Vehicle adaptation refers to the technical complexity of adapting vehicles to use a new fuel.

DME as a fuel in a diesel engine provides a lower noise level in comparison with a traditional engine. The engine can also provide higher torque (rotational force) at start-up to optimise driveability (Volvo, 2012). Diesel engines will continue to be required for heavy-duty applications and can be modified to run on up to 100% DME (SHV Energy, International DME Association, 2020).

rDME can be used as a replacement for diesel in engines, requiring only an inexpensive retrofit to the vehicle. This solution provides a valuable renewable fuel option for the hard-to-decarbonise heavy-duty transportation sector (SHV Energy, International DME Association, 2020).

Volvo Trucks is one of the few companies with customer experience involving Liquefied Natural Gas (LNG), Compressed Natural Gas (CNG) and DME fuels within their vehicle range. While use of CNG and LNG required a different (spark ignition) engine and numerous resultant changes to maintenance, safety, refuelling and other elements, few changes were required for DME vehicles as they retained the same (compression ignition) diesel engine, significantly reducing the cost of switching to the new fuel and improving customer acceptance from drivers and fleet owners) (Kidder, 2021).

Diesel, HVO and methanol for instance are suitable for all heavy applications, without any special vehicle adaptation required. On the other hand, DME, whether it is grey or green, is suitable for most applications with no expensive or extensive vehicle adaptation required (Volvo, 2015). Table 11 summarises the vehicle adaptations required for each alternative.

[6] *Typical value is EU mix. The variation between best and worst case for the renewable fuels depends on which feed - stock they are produced from. For example, the best case for DME, Synthetic Diesel and Methanol is black liquor while the worst case is wood. The best case for electricity is wind, solar and water and the worst case is coal (Volvo, 2015).*

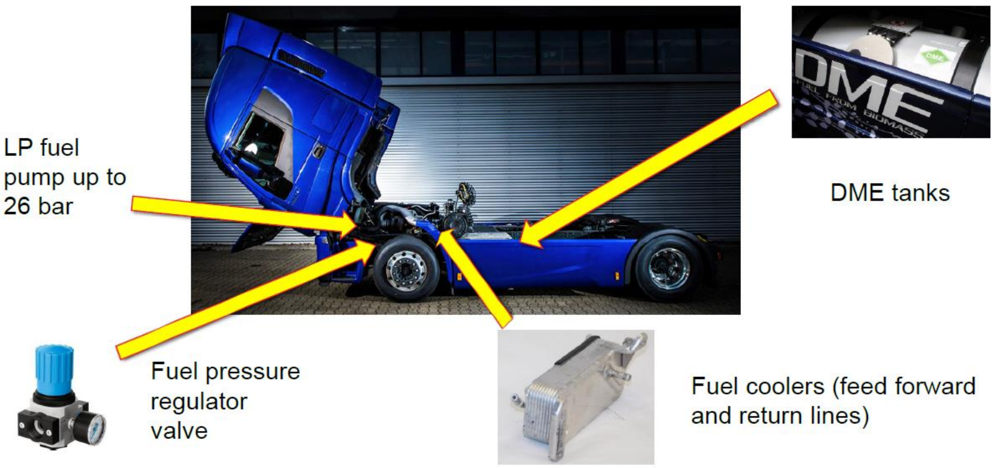
Table 11: Vehicle adaptation Ranking, Volvo 2015

Suitable for all heavy applications; no special vehicle adaptation required	Suitable for most applications; no expensive or extensive vehicle adaptation required	Suitable for most applications; expensive and extensive vehicle adaptation required	Suitable to up to half of all applications; complex expensive and extensive vehicle adaptation required	Suitable for only a limited number of applications; major, expensive and extensive vehicle adaptation required
Diesel, Biodiesel, HVO	**DME**, Methanol, Ethanol	/	Natural gas, Electricity, Other biofuels (CBG, LBG)	/

Major challenges for the use of DME as a fuel are the storage and transportation, which can be difficult due to the gaseous nature of DME.

Stephane Marie-Rose explained the adaptations needed to vehicles: technology-wise, the injection head of the vehicle must be modified, as well as the tanks, since a pressurised tank is required. Pressurising DME, however, is problematic for injection seals in the long term and requires minor modifications to the engines. Apart from the tank and injector changes, no other major changes are required (Marie-Rose, 2021). Figure 31 from FPT Powertrain Technologies and Iveco Group illustrates the vehicle modifications in a truck modified to run on DME.

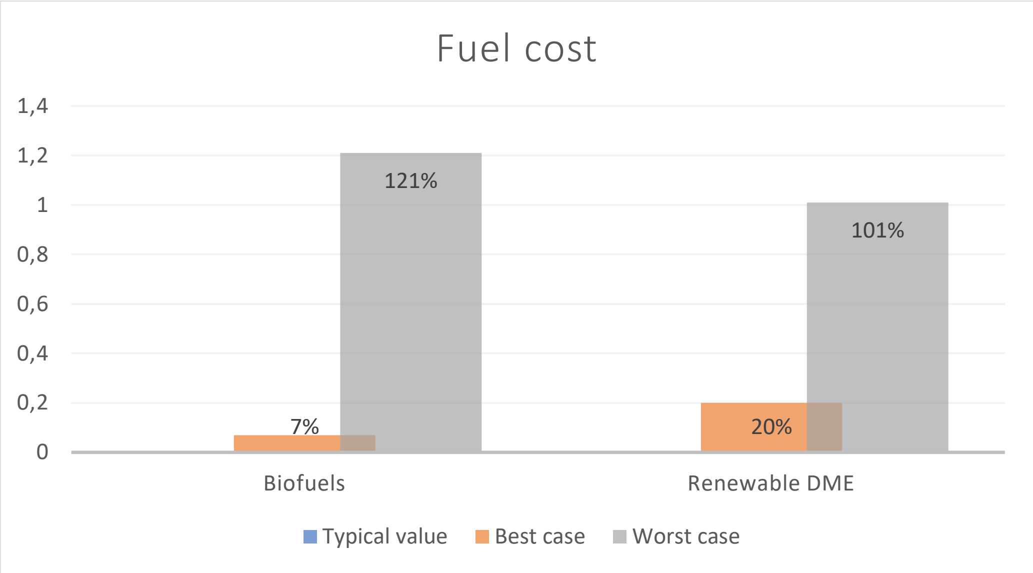
Figure 31: Necessary vehicle modifications based on standard diesel version (Daniel Klein, 2022)



3.1.1.1.3.5 Fuel cost

The evaluation of fuel cost includes raw material costs, fixed and variable production costs, transport and infrastructural costs, and the cost of energy utilisation in the distribution chain. In Figure 32, the costs of rDME and biofuels are expressed in comparison to diesel: rDME could be 20% to 101% more expensive than diesel.

Figure 32: Fuel cost increase compared to diesel (Volvo, 2015)[7]



DME price varies depending on the industry: in the fuel industry, the **price of DME is based on its energy value on the natural gas reference.** A new way to index DME fuel to a product closer to its use in terms of energy value should however be found (Marie-Rose, 2021).

The major barrier for uptake is that the price of DME as a fuel for trucks is too high: therefore clients are not willing to pay more for it. Additionally, some of them expect a payback period of less than 10 years and a return of investment of more than 50% (Marie-Rose, 2021) (Kisurin, CEO Aerosolex, 2021). At Aerosolex, long-distance deliveries also increase the costs, it is therefore advantageous to focus the supply on local markets (Kisurin, CEO Aerosolex, 2021).

In the end, considering the transport, production and market sales cost, DME will reach about 2.5 times the price of methanol. Depending on the energy value, there are several barriers from an economic point of view, noting that the Life Cycle Analysis of both DME and methanol should also be considered as methanol can also be produced from different sources (grey, green etc.) (Marie-Rose, 2021).

While **the price of DME is higher than that of traditional fuels**, it will allow CO_2 emissions to drop drastically. Since trucks are penalised for their high amount of CO_2 emissions, the amount of CO_2 emissions avoided must be included in this calculation. For example, based on the distance travelled by a truck in km, an amount of carbon tax could be paid to subsidise the amount of CO_2 that will enter the market. If such a process is applied, the cost of DME could be decreased (Marie-Rose, 2021).

3.1.1.1.3.6 Fuel infrastructures

Fuel infrastructure defines the speed and ease for a new fuel to be introduced and integrated within existing systems (Volvo, 2015). Table 12: Fuel infrastructure ranking, Volvo 2015 that DME requires more infrastructural changes than diesel or methanol.

[7] *Typical value is EU mix. The variation between best and worst case for the renewable fuels depends on which feed - stock they are produced from. For example, the best case for DME, Synthetic Diesel and Methanol is black liquor while the worst case is wood. The best case for electricity is wind, solar and water and the worst case is coal (Volvo, 2015).*

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Table 12: Fuel infrastructure ranking, Volvo 2015

No changes (liquid fuel)	Minor changes (liquid fuel)	Major changes (liquid fuel)	Gas handled in liquid form at low pressure	Gas handled under high pressure or in liquid form at low temperature
Diesel, HVO	Biodiesel	Methanol, Ethanol	**DME**	Natural gas, Electricity, Other biofuels (CBG, LBG)

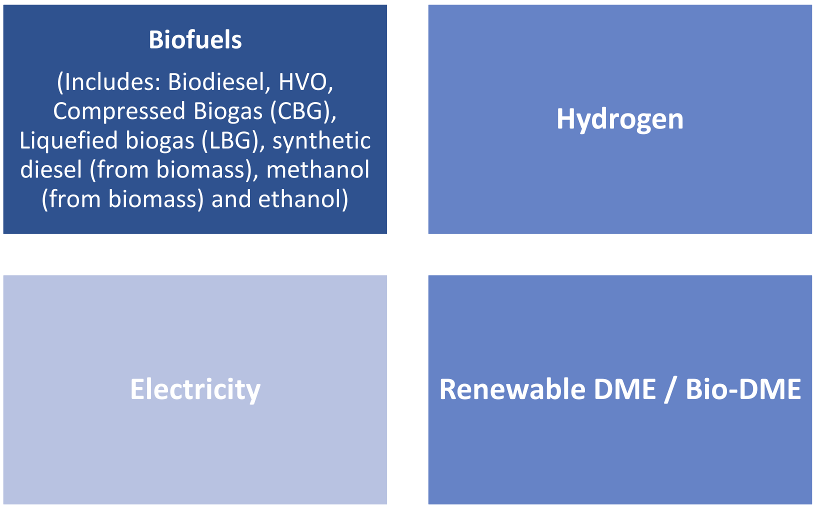
If DME is compatible with LPG fuelling stations, one major challenge to use widely DME as a fuel is the lack of LPG fuelling stations for high scale implementation in European countries (Willems, 2021).

In Germany (Aachen), a joint initiative between Ford and Primagas built and operates a rDME filling station, the first in Germany, which did not require any substantial redesign of the existing infrastructure. This fuel has been used by Ford, as part of the C3-Mobility project, to develop vehicles which can run on 100% rDME (Primagas, 2021).

3.1.1.1.3.7 Comparison of DME with other alternative fuels

While diesel is the most widespread fossil-based energy that is used in HDVs, several alternative power sources can be used to power HDVs. The alternatives in Figure 33 were identified as other options that are being considered for trucks:

Figure 33: Main alternative power source possibilities for HDVs



According to Volvo Trucks, **DME is among the most promising fuels for trucks** along with HVO and electricity, and is a strong long-term candidate with low-climate impact and efficiency benefits.

Table 13 summarises the performance of alternative fuels for trucks in comparison to diesel, based on the criteria studied in the previous section (Volvo, 2015).

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Table 13: Comparison of alternative fuels for trucks (Volvo, 2015)

Fuel	Climate impact[8]	Energy efficiency[9]	Fuel potential[10]	Vehicle adaptation (trucks)[11]	Fuel cost[12]	Fuel infrastructures[13]
Diesel	/	35%	/	5/5	/	5/5
Biofuels	Between -32% and -95%	Between 7% and 36%	11%	Between 2/5 and 5/5 depending on biofuels	Between +10% and +101%	Between 1/5 and 4/5 depending on biofuels
Electricity	Between +60% and -100%	Between 12% and 75%	/	2/5	/	1/5
Renewable DME / Bio-DME	Between -89% and -94%	20%	19%	4/5	Between +20% and +101%	2/5
Most advantageous option for each criterion	DME	Diesel & Natural gas	/	Diesel & HVO	Diesel	Diesel

Research about the decarbonisation of HDVs has also focused a lot on electrification and hydrogen. Some promising results are expected in terms of energy efficiency from electricity and from some biofuels (e.g., biodiesel and HVO). A Battery Electric Vehicle (BEV) is indeed roughly twice as energy efficient as a Fuel Cell Electric Vehicle (FCEV) (95% and 52% fuel production efficiency respectively). However, for buses and trucks, an FCEV is roughly 30 to 40% more energy efficient than a diesel vehicle (Christensen J. , 2021).

Long-haul trucking, however, remains a challenge for electricity-powered trucks, whether they are BEVs or FCEVs powered by hydrogen, as the far higher weight and longer distances do not guarantee the same autonomy as in the field of passenger cars: for instance, Volvo's electric heavy duty truck model, the Volvo FH Electric, boasts a range of up to 300 km, with a battery capacity between 180 and 540 kWh and a Gross Combination Weight (GCW) of up to 44 tonnes. In comparison, Volvo's diesel-powered long-haul-focused truck, carrying the same GCW, can be optimised to have a range of up to 1,000 km (Girteka Logistics, 2021).

Moreover, there is not a sufficient quantity of batteries to sustain a huge fleet renewal of electric trucks (Girteka Logistics, 2021). The high cost of the required lithium-ion batteries is one of the main obstacles: The battery pack is currently estimated to be \$200 per kilowatt-hour. Even with \$100 per kilowatt-hour, a 500-kWh battery pack would cost \$50,000, which represents about 30% the cost of a conventional truck (Arar, 2020)

> *"The internal combustion engine powertrain industry was already struggling before the Covid-19 crisis, and it has gotten even worse since. For the decarbonisation of heavy-duty vehicles, electrification has really gotten a lot of attention. Anyone who we speak with from the industry says that it just doesn't make any sense at the moment to run heavy-duty electrified vehicles (whose weight is an important commercial and legal factor).*

[8] Reduction/increase of CO_2 emissions compared with conventional diesel fuel
[9] Proportion of energy reaching the vehicle's driven wheels
[10] % of the total energy demand for transport in Europe that can be covered by each alternative
[11] Overall assessment of the technical complexity of adapting vehicles to use the new fuels
[12] Fuel cost increase compared to diesel
[13] How quickly and easily a new fuel can be introduced and integrated with existing systems.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

The batteries themselves are so large and so heavy that weight and space considerations become a concern." (Kidder, 2021)

Regarding hydrogen trucks autonomy, it currently ranges between 300 and 500 km, but the most ambitious prototypes expected to arrive on the market by 2030 are expected to surpass 1000 km.

The defossilisation of the transportation sector would require several low carbon fuels.

It is however important not to consider these alternative power sources as competitors of DME, but rather complementary solutions to achieve decarbonisation and/or reduce the dependence on fossil energy sources. As several different solutions are needed to achieve GHG reduction goals in the next decades, there might not be competition between different low-carbon energy sources or technologies.

To fight global warming, we need to look at all options. Renewable fuels offer a lot of opportunities (Willems, 2021)*."*

"Every solution is required and should be exploited to its maximum." (Werner Willems, 2022)

According to Ford, substituting fossil energy carriers with non-fossil alternatives will require more than one technical solution in order to decarbonise transport for new and existing vehicles. Defossilisation of existing vehicle fleets is required as quickly as possible in order to meet 2030's 1.5° GHG-Budget. Synthetic low carbon fuels, in particular for legacy fleets are therefore crucial (Werner Willems, 2022). However, current EU regulations are not in line with this vision.

3.1.1.1.4 Policy implications to introduce DME as a fuel in the transportation market

Regulatory barriers to develop DME as a fuel in the transportation sector in Europe:

The most important barrier for the automotive industry to invest in DME or e-fuel vehicles is regulatory because DME powered vehicles are not allowed in Europe as there are no standards or regulations surrounding their use (Willems, 2021).

The **phase-out of fossil fuel vehicles**, which implies the ban of combustion engines[14] by 2035 in several European countries, prevent e-fuels (and therefore DME) from being used in the transportation sector. In June 2022, the European Parliament proposed this ban, despite strong opposition (Vie Publique, 2022). The environment ministers of the EU-27 however agreed to reconsider the issue of plug-in hybrids and synthetic fuels in 2026 in the light of technological developments (Feitz, 2022).

This phase-out might have an impact on non-European geographical markets as well. Indeed, European policies have an impact on the global market. For example, in South Korea, new regulations restraining the use of DME as a fuel were implemented only after Europe set the 2.6% ratio for low carbon fuels (Cho, CEO Bio Friends, 2021).

According to eFuel Alliance experts, the automotive industry will not be incentivised to invest in DME or e-fuels as long as this ban remains. The organisation advocates to consider renewable fuels in the energy mix for the transportation sector. In North America, the use of DME as a fuel is however more incentivised.

Also, government intervention is key to create incentives for DME as a fuel and decrease its price: currently, DME is more expensive than existing fuels and therefore would fail to attract consumer interest.

[14] The 2035 phase out date will apply to rigid vehicles with a gross vehicle weight less than or equal to 26 tonnes, and any articulated HGVs with a gross combination weight of 26 tonnes and under. It therefore includes HDVs (Department for Transport UK Government, 2022).

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

"I believe in DME as a fuel only if government supports it. If not, there will be no future for DME." (Kisurin, CEO Aerosolex, 2021).

"In Germany, politicians are focused on electricity or hydrogen, but DME is not under discussion. If there is any switch, it will be related to politics rather than technical advances." (Anonymous expert, 2021).

"The state of California has given strong incentives for it, but in Europe there is no lobby for it." (Anonymous, 2021).

3.1.1.2 Shipping, a niche market for diesel replacement

Between 2012 and 2014, a project called SPIRETH (Alcohol (spirits) and ethers as marine fuel) took place, the goal of which was to test methanol-based fuels, including DME in a full-scale pilot project to contribute to finding the best environmental and economic alternative for a sustainable and successful maritime transport industry. Project results showed that methanol and DME-based fuels are viable alternatives for reducing emissions from ships. Methanol showed fantastic pilots, leading to investments rising for its use as a marine fuel. DME was rated more poorly, given the risk it posed onboard as a heavier-than-air fuel, considered unacceptable in enclosed environments such as onboard ships. No major progress for DME as a ship fuel are expected, as methanol is seen as a better alternative than DME (Kidder, 2021).

According to Gilles Hardy, the major barrier preventing DME to enter the maritime industry is the very low availability of the fuel: as a large container ship engine requires around 18,000 tonnes marine diesel energetic equivalent of fuel per year, there is not enough DME, and even less rDME available to meet their requirements. The possibility of ships running on 100% DME appears plausible in the short- and medium term because the DME availability would have to be multiplied by a factor 100, which would not be feasible within the next few years. This would, moreover, only be feasible with the support of the methanol industry. On the other hand, ammonia or methanol could be ignited with a certain amount of pilot DME injected to replace diesel in ship engines, representing 5% to 10% of the total energy input (Hardy, 2022).

3.1.1.3 DME to be used in machines in the agricultural sector

The energy consumption of the agricultural sector in the EU accounted for 3.3% of final energy consumption in 2019, with the highest shares of agriculture in energy consumption found in the Netherlands (8.9%) and Poland (5.5%). The majority of the direct energy use in agriculture comes from non-renewable sources, in particular from on-farm diesel use. According to Eurostat, energy use in agriculture coming directly from oil and petroleum products represented a share of 55% in 2019, significantly contributing to the carbon emitted by the agricultural industry (Eurostat, 2021). Nowadays, diesel engines power most of the agricultural equipment around the world which is necessary to grow, harvest, process and deliver crops to the market and its consumers. On-farm diesel is used to fuel tractors and other vehicles, pumps, machinery and remote electricity generators. Most of this diesel is associated with tractor use, with an estimated 10 million tractors used for agricultural activities in the EU-28 (Paris, et al., 2022).

These diesel engines used in off-road and heavy machinery applications can be modified to run on up to 100% DME (SHV Energy, International DME Association, 2020). However, a lack of regulation clarity regarding off-road vehicles and agricultural equipment represents a barrier to the adoption of DME fuel in agriculture (Ralf Diemer T. B., 2021).

Green Futures Inc conducted a pilot using a DME and diesel blend for the agricultural sector in India, through a proof-of-concept plant funded by the Indian Oil Corporation (Apte, 2022), as illustrated in Figure 34.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Figure 34: Pilot plant near Pune (India) demonstrating DME manufacture & use (Apte, 2022)

Being used as diesel substitute in tractors and heavy machinery is not the only potential application of DME in agriculture. According to Bio Friends, DME has a potential to be useful in smart farming which is an emerging concept in the agriculture sector. Smart farming consists of managing farms using technologies like internet-of-things (IoT), robotics, drones and artificial intelligence (AI) to increase the quantity and quality of products while optimising the human labour required by production. This concept has been growing in importance in recent years due to the combination of the expanding global population, the increasing demand for higher crop yields and the need for using natural resources efficiently. However, the implementation of all these digital technologies means that smart farming will need to go hand in hand with increased electrification to power all the computers and the wide range of sensors. DME could be used to generate this increasingly needed electricity via the implementation of hydrogen fuel cells. After being produced and stored, DME could be converted into hydrogen through a simple, inexpensive process compared to natural gas to hydrogen conversion (Oberon Fuels, 2021). This hydrogen could in turn be used in fuel cells to generate electricity which could be fed into the smart farms.

For example, since June 2022, Bio Friends has built a smart farm to demonstrate "DME-to-H_2 Reforming & Fuel Cell system". The tests for cultivation will end in December 2023. Through this project, Bio Friends distributes sustainable DME fuel to agricultural areas where natural gas is not supplied. A DME fuel cell is installed at a smart farm to provide energy solutions through electricity, cooling/heating and CO_2 farming. DME accounts for 30% of energy source in these smart farms and smart barns as an agricultural fuel (Cho, DME, rDME and H2 Business in Korea, 2022). Figure 35 is an illustration of the smart farm infrastructures installed by Bio Friends. Figure 36 and Figure 37 describe further the process used by Bio Friends in the agricultural sector.

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Figure 35: Installation of “DME-H2 FC System” and “DME Power Gen.” by Bio Friends (Cho, DME, rDME and H2 Business in Korea, 2022)

Figure 36: Process from the DME plant to the Smart farm (Cho, DME, rDME and H2 Business in Korea, 2022)

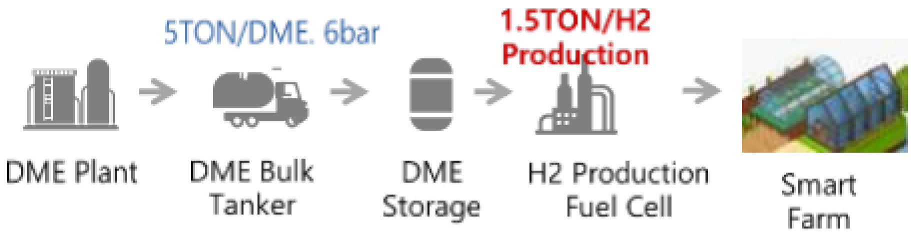
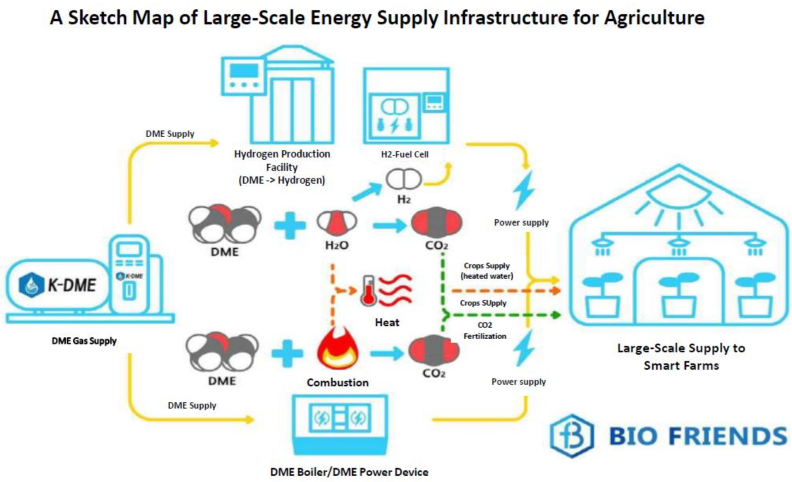


Figure 37: Hydrogen production technology from DME fuel (Cho, DME, rDME and H2 Business in Korea, 2022)



3.1.2 Segment 2: DME LPG blend

Liquid Petroleum Gas (LPG) is a liquid gas that is primarily used as a fuel for transportation (Autogas), domestic and commercial cooking and heating. LPG can be blended with DME providing an opportunity to employ clean LPG. For example, blending DME with LPG would constitute a cleaner, more affordable and inclusive option for off-grid EU rural areas than LPG (SHV Energy, International DME Association, 2020) (Jacobsen, 2022).

Alternatives such as electrification (heat pumps) or hydrogen that could be part of the solution for decarbonisation will yet require more time, considerable investments, and will need to overcome natural limitations (e.g., energy density). rDME instead is an optimal solution as the gas is largely available, the infrastructure already exists and blending it with DME makes LPG considerably more sustainable (Jacobsen, 2022).

Link to demonstration of gas burner running on DME-LPG blend in India- https://youtu.be/0Uo7JHRL_qU

3.1.2.1 rDME LPG blend market opportunity

DME is raising the interest of several LPG industry leaders, as they move forward with different projects and partnerships, as illustrated in Figure 38.

Figure 38: rDME projects of LPG industry leaders (Nikos Xydas, 2022)

For example, Suburban Propane took a 39% stake in Oberon in 2020 in order to support and accelerate the commercial development of rDME products. This partnership between Oberon and Suburban Propane allowed Oberon to produce the first commercial rDME in the US in 2021 (Dagan, 2022) (Figure 39).

Figure 39: Propane + rDME plant by Suburban Propane and Oberon Fuels (Anise-Hicks, 2022)

"rDME is a game changer for our industry" (Munson, Renewable DME Positioning your company as a sustainability leader, 2022).

There are two possible types of integrations of rDME in the LPG industry:

- The drop-in form, which is used to blend rDME with LPG, requires no changes to infrastructure, equipment and appliances.
- The non-drop-in form implies that rDME is used at 100% to replace LPG application and "pure" rDME is used. This form requires considerable changes to infrastructure, equipment and appliances (Nikos Xydas, 2022).

Renewable DME can be blended with LPG to move towards the carbon neutrality of the LPG industry. Despite being cleaner than oil and coal, there is a lot of demand around the world to make LPG more sustainable. rDME can be easily distributed using the existing LPG infrastructure at the same pressure. Similar to LPG, it drastically reduces pollutants such as NOx, SOx and particulate matter compared to solid and liquid fuels (Jacobsen, 2022).

Renewable DME can be blended at 20% with LPG or bioLPG and it can be used in any application where LPG is used, enabling a further reduction in GHG emissions (SHV Energy, International DME Association, 2020) (Munson, Vice President Oberon Fuels, 2021) (Jacobsen, 2022) :

- Agriculture and farming;
- Heating & cooking;
- Commercial;
- Industrial applications;
- Mobile & recreational;
- Forklift trucks;
- Transport.

Depending on the market segments, rDME can be used in blended applications with LPG or pure applications (100% replacing LPG. For each tonne of LPG that is replaced by 100% rDME, carbon intensity can mostly be reduced by 80 to 100%. For each tonne of LPG that is replaced by a 20% rDME-LPG blend, the carbon intensity is reduced by 11 to 14% (Nikos Xydas, 2022).

Not only does DME reduce the carbon intensity of propane, but its easy handling properties also make fuelling and infrastructure relatively simple and inexpensive (Oberon Fuels, 2021). Additionally, bio-LPG is available in limited quantities whereas methanol-based DME is easily scalable and available in large quantities (Willems, 2021).

3.1.2.2 Market attractivity for LPG blending in transportation

LPG is the number one alternative fuel in the EU, counting 8 million vehicles and 31,000 fuelling stations, Poland, Germany and Italy being the EU countries with the most LPG stations and vehicles (Liquid Gas Europe, 2020). The wide and global LPG network could be leveraged to move to green hydrogen (Anise-Hicks, 2022).

While the original focus of DME in transportation was 100% DME in a diesel engine, DME as a blending component is attracting more and more investment by the LPG industry (Kidder, 2021). For example, SHV Energy and Primagas are currently investing in DME production for LPG blending and the LPG industry is willing to invest in LPG stations (Willems, 2021). In the US, Suburban Propane, an LPG distributor, has announced the commercial launch of a new product: a blend of LPG and rDME to be used as a drop-in replacement for propane engines in both on-road and off-road applications (Suburban Propane, 2022).

According to the eFuel Alliance, whilst some transport modes can be electrified, many forms of transport will continue to require a chemical energy source. Renewable DME can be used as a blend in an existing vehicle fleet with little modification (SHV Energy, International DME Association, 2020). DME is indeed chemically similar to LPG: it is a gas at room temperature and pressure, and like LPG, it is easily transported as a liquid in pressurised cylinders and tanks.

Vehicle refuelling can therefore be carried out using a typical Autogas dispenser with few modifications. Refuelling is also quick and convenient (SHV Energy, International DME Association, 2020). The infrastructure for DME and LPG blends already exists, which is a major opportunity for the use of DME in transportation.

"*The obstacle for introducing a new fuel, whether it was LNG or CNG or any alternative fuel, was always the infrastructure. However, the DME infrastructure for handling, distribution, and fuelling exists everywhere. It is the LPG infrastructure. The infrastructure is already there practically everywhere, it is well understood and available from numerous companies."* (Kidder, 2021).

"The LPG market is a nice sector to be for DME at some point." (Marie-Rose, 2021) According to Cinch Munson, "DME used as LPG blend is the most important DME segment in the US and it represents considerable opportunities, especially in California where it is driven by specific incentives in transportation" (Munson, Vice President Oberon Fuels, 2021).

In addition, several adaptations of the infrastructure would be required. According to Lizzie German, DME is more chemically aggressive towards rubbers, plastics and non-metallics in comparison to LPG. Some equipment would need to be changed to be more DME compatible. SHV is already working in collaboration with Ford for the distribution of DME in Germany (German, 2021).

3.1.3 Segment 3: Hydrogen carrier

3.1.3.1 *Potential of DME as a hydrogen carrier*

"Organisations like Oberon Fuels and Bio Friends are currently working in the area of DME as a hydrogen carrier"" (Kidder, 2021) (Cho, CEO Bio Friends, 2021).

Renewable dimethyl ether (rDME) is an excellent carrier molecule to transport hydrogen to power fuel-cell electric vehicles and to provide increased supplies of renewable hydrogen. With six hydrogen atoms in each DME molecule, DME is indeed particularly dense in hydrogen (Oberon Fuels, 2021). A litre of liquid DME (or methanol that can be converted into DME) contains more hydrogen than a litre of liquid hydrogen (SHV Energy, International DME Association, 2020).

"*I would say the newest interest in DME would also be its use as a hydrogen carrier. A litre of DME holds more hydrogen than a litre of hydrogen, making DME an excellent carrier of energy* (Kidder, 2021)."

In comparison to hydrogen, DME present key advantageous characteristics:

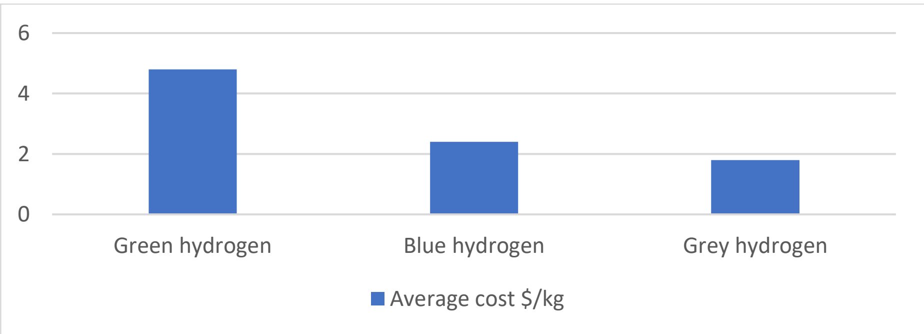
- DME liquefies at low pressure (~73 psi), making it much easier and less expensive to transport than hydrogen, which can be compressed at up to 10,000 psi of pressure.
- Converting DME into hydrogen is a simple, inexpensive process compared to natural gas to hydrogen conversion.
- Altogether, rDME overcomes some of the biggest barriers inhibiting the widespread use of hydrogen for transportation fuel, including access to renewable feedstocks; modular, scalable production; and energy-dense, cost-effective storage and transport.

"With a single molecule, we can not only reduce carbon emissions from transportation today, but also accelerate the development of the hydrogen economy and a net-zero carbon future" (Oberon Fuels, 2021)

3.1.3.2 *Hydrogen costs*

Hydrogen prices depend on the energy source (Marie-Rose, 2021). Green hydrogen produced with renewable resources costs between about \$3/kg and \$6.55/kg, fossil-based hydrogen costs about \$1.80/kg, and the cost of blue hydrogen, which pairs carbon capture with steam methane reformation of natural gas, is estimated at about \$2.40/kg (DiChristopher, 2021) (Figure 40).

Figure 40 Average hydrogen costs in 2021



3.1.3.3 Future of hydrogen in transportation

According to Kisurin, hydrogen does not have a future in the transportation sector, not only due to the challenges of hydrogen storage, but also due to the challenging implementation of new infrastructure required (Kisurin, CEO Aerosolex, 2021).

DME could however accelerate the development of the hydrogen economy and a net-zero carbon future (Oberon Fuels, 2021). While Wonjun Cho agrees that hydrogen for transportation is challenging due to the difficulties of production and storage, they believe in a future for hydrogen. Green hydrogen production indeed does not emit CO_2, which is a major environmental advantage.

"*The future of heavy-duty trucking will be hydrogen, but as it will take time to reach due to the difficulty to produce, carry and store hydrogen, DME will be the bridge to the future hydrogen society and a great source for opportunities*" (Cho, CEO Bio Friends, 2021).

3.1.4 Segment 4: Aerosol

3.1.4.1 Potential of DME as aerosol propellant

As of today, DME is most commonly used as a propellant for aerosol products such as spray-cans (Volvo, 2012). Aerosol propellants are compressed as liquified gases in containers and are then released in the air in the form of mist, foam, semi-solids or liquid. Various applications exist: They are massively consumed in the manufacturing of personal care products, such as deodorants, antiperspirants, hair mousses, hair sprays but can also be used in household products such as insecticides and air fresheners, as well as in medical application, such as in metered dose inhalers (Ahuja & Singh, 2021). Most professional hair sprays use pure DME as a propellant instead of propane or butane. DME provides much smaller particle size and quick drying, with no unpleasant smell. Aerosol paints applications are also relevant for automotive, art and crafts, footwear and others. DME enables an increase in pigment content while decreasing solvent content. The final product achieves superior quality with nearly the same cost (Kisurin, DME production, supply and market perspectives, 2022).

3.1.4.2 Overview of the market for DME as an aerosol propellant

The global and European DME market is mostly composed of aerosol propellants (Marie-Rose, 2021). In 2020, the global market for aerosol propellants was around USD 22.82 billion and is expected to expand through 2027 to reach USD 34.74 billion, led by robust demand in personal care products (Ahuja & Singh, 2021). As of 2020, Europe is holding the largest share in the global market (up to 30%) and is expected to pursue this growth through the presence of several established market players in the region, such as Royal Dutch Shell Plc (Netherlands) and Arkema Group (France), and the increasing demand for aerosol propellants from the personal care and cosmetic product industries in the region. The aerosol propellant industry is competitive and includes various market players. DME market players on the aerosol propellant market are mainly traditional DME producers that have been established for several decades or more. Since aerosol market players do not expect to rely solely on the market growth, companies are focused on strategic acquisitions to increase production capacity and expand global reach.

According to the International DME Association, until recently, producers of traditional DME have appeared to be reluctant to explore potential markets for DME other than chemical and aerosol applications (Kidder, 2021). DME producers are not typically interested in the use of DME as a fuel despite the fact that DME used for transportation has the same molecular composition and the same properties as DME used for aerosol. The current DME market is a stable market making modest commercial quantities of DME for use as an aerosol. Some DME players believe that if the market of DME drastically grew due to the adoption of DME as an alternative for diesel, the new size of the market

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might negatively impact the current market with the margins and the prices not suiting their models anymore (Kidder, 2021).

According to Ivan Kisurin, DME is a small market as EU countries buy less than 500 tonnes of DME a year. Due to the Covid-19 crisis, the European DME market faced challenges, with the DME demand decreasing to the point of overcapacity, where the DME production exceeded the demand (Kisurin, CEO Aerosolex, 2021). Despite this slight decrease, the aerosol market is by and large stable (Anonymous expert, 2021) and is expected to recover from the sanitary crisis to grow further in the future. DME only represents a finite share of the total aerosol market. In South Korea for example, while the market of aerosol reached USD 70 million in 2019, DME occupied USD 15 million, a 21% share. 70% of DME produced in South Korea is however used for aerosol. Between 2020 and 2025, DME is expected to grow at a rate of 14% to reach 35% of the domestic aerosol market (Cho, CEO Bio Friends, 2021).

The most preferred aerosol propellants are liquefied gases, and naturally occurring hydrocarbons, such as propane and butane, the latter of which is the main competitor for DME in the aerosol market, as it is a more affordable alternative (Kisurin, CEO Aerosolex, 2021). Other types of aerosol propellants include hydrofluorocarbon (HFC) and hydrofluoro-olefin (HFO). The usage of propellants, such as chlorofluorocarbons (CFC), HFC and hydrochlorofluorocarbons (HCFC) are now closely monitored by government and environmental agencies as they harm the ozone layer. Aerosol propellants must meet strict VOC (volatile organic compound) regulations. Since the introduction of these measures, the market of DME in aerosol products has increased due to the properties of DME complying with these regulations.

3.1.5 Segment 5: DME as a Chemical solvent

As DME can be used as a solvent in chemical applications, the chemical solvent segment also represents an important part of the DME market (Kidder, 2021) (Marie-Rose, 2021). According to Wonjun Cho, refrigerant and foam are however secondary market segments for DME (Cho, CEO Bio Friends, 2021).

For example, DME can replace Freon™ refrigerants from the Chemours Company. In 2019, the South Korean refrigerant and foam market represented USD 150 million, of which 2 million (1%) is DME. Additionally, by the end of 2023, 40% of current refrigerants will have to be replaced because of national regulations, constituting a considerable future market opportunity for DME (Cho, CEO Bio Friends, 2021).

DME can be used in the following industries as chemical solvent for:

- Construction materials (polyurethane foam, foam cleaners, foamed thermal insulating materials, extruded polystyrene). For example, Aerosolex has developed a non-toxic and environmentally friendly solvent and propellant for polyurethane foam production, reducing the prepolymer viscosity while increasing the pressure in the spray;
- Paints and coatings (varnishes, enamels);
- High quality solvent for the production various extracts and essential oils and for the extraction of active substances from plant- and animal-derived raw materials, reactive chemicals for chemical synthesis in laboratories;
- Production of health care products (freezing, component for wart removers);
- Refrigeration equipment (cooling agent for industrial and domestic refrigerating units, air conditioners);
- Metal and machine industry (a component for special welding and brazing gases, a chemical reagent for surface-degreasing products); and
- In the food and beverages industry (carbonated drinks, preservatives) (Aerosolex, 2022).

3.1.6 Segment 6: Power generation

DME could also be used to produce electricity. As a storage material, DME has the capacity to overcome the intermittency problem of renewable energy. However, there is no clear benefit of using DME for power generation since this would mean starting with electricity and water to go through a conversion step to produce electricity again, while incurring loss of energy efficiency along the way. Therefore, DME for power generation should not be pursued (Joost Smits, 2020). While it was the original interest in DME's potential as a fuel, large scale power generation is not currently a major driver of DME use in the market (Kidder, 2021).

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3.2 DME market players

The DME landscape is composed of a multitude of stakeholders, from longstanding global industry leaders to recently founded enterprises. Some players are specialists (only producing DME), while others produce a variety of chemicals, among which DME.

While Oberon Fuels and Bio Friends are the leaders for renewable DME, some recently established enterprises are coming into this market. Very few market players produce both DME and renewable DME (e.g., Nouryon).

Table 14 lists all organisations involved in the production of traditional DME and Table 15 is focused on rDME producers. The full list and characteristics of DME market players is provided in Appendix 1.

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Table 14: Major traditional DME producers across the world (Methanol, Coal, Natural gas and Syngas based DME)

	Aerosol propellant	Chemical Industry	Transportation Fuel	LPG Blending	Unknown applications
Europe	Shell Nouryon PCC Group GRILLO	Air Liquide Nouryon PCC Group			multigas
Asia	AEROSOLEX MITSUBISHI GAS CHEMICAL	CEEC 中国能建 ENERGY CHINA AEROSOLEX	CEEC 中国能建 ENERGY CHINA JOVO MITSUBISHI GAS CHEMICAL	CEEC 中国能建 ENERGY CHINA JOVO MITSUBISHI GAS CHEMICAL	中国神华 CHINA SHENHUA
North America	Chemours				
Latin America	THE NATIONAL GAS COMPANY OF TRINIDAD AND TOBAGO LIMITED	THE NATIONAL GAS COMPANY OF TRINIDAD AND TOBAGO LIMITED		THE NATIONAL GAS COMPANY OF TRINIDAD AND TOBAGO LIMITED	

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Table 15: Major sustainable DME producers across the world

Sustainable DME producers	Aerosol propellant	Chemical Industry	Transportation fuel	LPG blending	Off-grid energy market[15]
Europe	Nouryon		Circular Fuels Ltd	Dimeta	Circular Fuels Ltd
Asia	BIO FRIENDS	BIO FRIENDS	BIO FRIENDS GREEN FUTURES INC	BIO FRIENDS	
Middle East and North Africa (MENA)	TARKİM				
North America		Enerkem	oberon FUELS	oberon FUELS	

[15] *Off-grid energy market includes off grid domestic, commercial and industrial heating and cooking, and transport.*

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4 Conclusion

In the context of defossilisation and decarbonisation of the economy, renewable DME use presents opportunities in the energy sector. While the current demand for DME is mainly focused on chemical solvent and aerosol propellant usages, the DME industry explores markets such as diesel replacement for trucks and agricultural machines, LPG blend for transportation, cooking and heating, and as a hydrogen carrier. However, while the infrastructure is a low barrier for DME deployment in the three latest segments, the demand in these segments would be able to get developed only if incentivised by policies and regulations which will unlock industrial shifts. On the supply side, innovative technology players, together with the LPG and automotive industries, continue developing R&D projects to build scalable pilots across the world.

If today our globalised economy is carbon intensive, electrification and then the probable shift to a hydrogen economy could be the next moves to defossilise and decarbonise at large scale. In this frame, DME could be considered as a way to transition from an intensive carbon economy to a hydrogen economy, as concluded Wonjun Cho.

Another way to look at the development of the DME market is to twin it with the development of the methanol economy (for shipping for example).

The analysis of the global DME market is a first important step to study possible exploitation routes of the CO2Fokus technology. Coming activities will be organised to build strategies to bring the designed technology to the market.

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6 Appendix

Appendix 1 - Main DME Stakeholders across the world

Large companies

Europe

Organisation	Country	Production Process	Usages of DME	Other energies produced ?	Regional market	Clients or client industry	Other
Air Liquide	France	Methanol based DME	Chemical solvent	/	Internal use only (Intermediate for chemical applications)	Internal use only (Intermediate for chemical applications)	
Grillo-Werke	Germany	Methanol based DME	Aerosol propellant	/	Europe	Hairspray and spray paint, foams	Medium size company
Multigas	Switzerland	Methanol based DME	Unknown	/	Switzerland & Europe	Unknown	
Nouryon	Netherlands	Methanol and Biomethanol based DME	Aerosol propellant, Chemical industry	/	Europe & World	Hair and paint spray, XPS (extruded polystyrene) industry, foams sprays	
PCC SE	Germany	Methanol-based DME?	Aerosol propellant, Chemical industry	Renewable energies	DME market : Russia (General : Global reach)	Beauty products (hairspray), Polyurethane construction foam	Production plant with an annual capacity of 20,000 tonnes.
Shell	UK / Netherlands	Methanol based DME	Aerosol propellant	Natural Gas, Petroleum, Diesel etc.	Global reach	Cosmetics and paint industry, foams and insulation boards, component for refrigeration fluids, production of Dimethylsulfat	

						e and many other technical areas	

North America

Organisation	Country	Production Process	Applications	Other energies produced ?	Regional market	Clients or client industry
The Chemours Company	USA	Unknown	Aerosol propellant	/	Global reach across 58 worldwide locations	Hair spray, deodorants, air fresheners, paints,

South America

Organisation	Country	Production Process	Applications	Other energies produced ?	Regional market	Clients or client industry	Other
National Gas Company of Trinidad and Tobago Limited	Trinidad & Tobago	Natural gas, methanol	Industry	Natural gas		Aerosol propellant, LPG blend	The Process Licensor for CGCL's DME Plant is Mitsubishi Gas Chemical Company, Inc. (MGC).

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Asia

Organisation	Country	Production Process	Applications	Other energies produced ?	Regional market	Clients or client industry	Other
China Energy Limited	China	Methanol based DME	Industry	Oil and gas	China	LPG Blending, Fuel distributors, Chemical producers	
Jiutai Energy Group	China	Methanol based DME	Unknown	/	China, Mongolia		
JOVO	China	Methanol based DME	Industry	LNG, LPG	China	LPG blending, Transportation	
KOGAS	South Korea	Syngas-based DME	/	LNG			
Mitsubishi Gas Chemical Co	Japan	Methanol based DME		/	Global reach (Asia, Europe, Caribbean)	LPG Blending, Aerosol propellant, Fuel, Power generation	Plant in Trinidad and Tobago: annual production capacity of one million tons of methanol and 20,000 tons of DME
Shenhua Ningxia Coal Industry Group	China	Coal based DME		Coal	China		

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n. 838061

Specialists

Asia

Organisation	Country	Production Process	Usages of DME	Other energies produced ?	Regional market	Clients or client industry	Other
Aerosolex	Russia	Methanol based DME	Aerosol propellant, Chemical industry	/	Russia, CIS and Europe	Cosmetic products, household chemicals, construction materials, paints and coatings, extracts production, laboratory, Production of health care products, Refrigeration equipment, Metal and machine industry, Fuel, Food and beverages	Industrial scale for our market - medium size capacity Biggest in Europe is 55.000 tons

Sustainable DME

Specialists

Organisation	Country	Type of DME	Production Process	Applications (Hydrogen carrier, fuel, solvent, aerosol, chemicals, heating, other)	Other energies produced ?	Regional market	Clients or client industry	Other
Bio Friends	South Korea	Bio-DME	Methanol and Bio-methanol based DME and Natural gas based DME (at big scale with KOGAS)	Aerosol Propellant (95%), Transportation (5%), + Farming tested in a feasibility study with Oberon, LPG blend	Hydrogen	South Korea, Indonesia, Turkey, Northern Europe	LPG bioDME fuels, refrigerant, aerosol , hydrogen source	5000 ton DME production plant, 2nd factory of BioDME: 10000 ton per tear manufacturing capacity Bio Friends is world leader: they are thinking about next stage of DME
Circular Fuels Ltd	UK	Renewable DME	Waste, biomass and residue feedstocks	Off-grid energy market : off-grid domestic, commercial and industrial heating and cooking, and transport.	/	UK	/	Joint venture between Dimeta and KEW Technology . The plant will have a production capacity of 50 kilotonnes

								of rDME per year from municipal solid waste.
Dimeta	Netherlands	Renewable and recycled carbon Dimethyl Ether ("rDME")	current partnership focussing on waste and biomass gasification, but all feedstocks and processes within scope	Energy (off-grid areas), LPG blend,	/			Joint venture established by SHV Energy and UGI International, global distributor for the LPG industry
Enerkem	Canada	Bio-DME	Bio-methanol based DME		Biofuels and renewable chemicals	Internal use only (Intermediate for chemical applications, Chemical feedstock, refrigerant)	/	Enerkem produces DME at big pilot scale (so high costs) - 50kg of methanol per hour in the reactor
Green Futures Inc	USA / India	Bio-DME	Waste based DME	Transportation and cooking fuel				
Oberon Fuels	USA	Renewable DME	Waste based DME : organic feedstock, Biogas (captured	Road transportation, Propane blending, Hydrogen carrier, Farming	/	USA	Farm, cities and businesses (buses, trucks companies such as Volvo,	

			methane emissions), Natural gas + CO2				Mack Trucks, car manufacturers such as Ford and FVV)	
Tarkim	Turkey	Green DME		Aerosol and insulation	Bioethanol	Europe		

DME process technologies

Organisation	Country	Production Process	Usages of DME	Comment
Haldor Topsoe	Denmark	Methanol based DME	Transport & Chemical applications (Research)	
Linde AG	Germany	Methanol based DME	Aerosol propellant, Refrigerant, Chemical industry	Owns PANGAS
Toyo Engineering Corporation	Japan	Methanol and coal based DME		

Potential DME producers

Organisation	Country	Type of DME	Production Process	Applications
ChemBioPower	Canada	Bio-DME	Biogas and biomass	Transportation, Propane Blending, Chemical industry
AR Challenges Ltd	Israel	Bio-DME	Waste based DME	Biojet fuels
FLEDGED Project	EU Project (7 countries)	Bio-DME		Transportation