ALGAESOL

Sustainable aviation and shipping fuels from microalgae and direct solar BES technologies

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Feedstock benchmark and technical specifications

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Executive summary

The present document (Deliverable D1.2 - Feedstock benchmark and technical specifications), reports the outcomes of WP1-Task T1.2, which defined the overall features of the project solar and algal sustainable fuels pathways. This executive summary outlines the second deliverable of the ALGAESOL project (D1.2), which focuses on a feedstock benchmark and the definition of the technical specifications of all the technologies involved in the project. D1.2 highlights the substrates to be used and/or modelled for the synthesis of sustainable aviation and shipping biofuels, both in terms of wastewaters and CO_2 sources. A review of the relevant literature for waste (gas and water) streams has been herein presented, to identify the substrates most suitable to achieve the sustainable aviation and shipping fuels previously characterized in the Deliverable D1.1. Furthermore, the technical specifications, streams and interactions between all the technologies involved in WP2 and WP3 have been specified in this early stage of the process, and a shared document between all partners has been produced as an outcome of task T1.2.

Deliverable D1.2 was prepared by UdG in close collaboration with the consortium partners (in particular NORCE and SIMTECH, with contributions of all technical partners). The outcomes of task T1.2 reported in this document will be relevant in the further definition of the process streams and for all tasks related to modelling and simulation, as both the feedstock database and the ALGAESOL technical specifications database served as a baseline also for the development of WP1-Task T1.3 and WP1-Task T1.4.

Abbreviations

The abbreviations relevant for WP1-T1.2, used in the ALGAESOL Deliverable D1.2 are listed in the table that follows.

Table 1: Abbreviations used in this document.

Abb.	Description	Abb.	Description
BES	Bio-Electrochemical System	NOx	Nitrogen oxides
CCUS	Carbon Capture Storage and Utilization	SOx	Sulphur oxides
EC	European Commission	SAF	Sustainable Aviation Fuel
EU	European Union	TN	Total nitrogen
GA	Grant Agreement	TP	Total phosphorous
GHGs	Green House Gases	WP	Work Package
HC	Hydrocarbons	WPx-Ty.z	Work Package x Task Ty.z
Mx	Project Month x	WW	Wastewater

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1. Introduction

Global fossil fuel overuse and increasing green-house gases (GHGs) emissions have intensified the study and development of alternative, renewable fuels, with the aim to meet future energy demand and satisfy present and future sustainability needs. Fossil fuels could deplete within the next 50 years, and severe environmental damages associated to climate warming could materialize, prompting organizations to target reductions of carbon emissions into the atmosphere, and begin a shift towards renewable energy sources in the last decades. Biofuels are considered renewable energy sources, and include products derived from biomasses or their residuals: such as biogas, biodiesel, bioethanol, biomethanol, bioethers, synthetic biofuels, biohydrogen, and vegetable-microalgal oils. Considering the current levels of production, markets seem primarily focused on biogas, biodiesel and bioethanol, which are already produced at industrial scale; but more innovative pathways need to be developed in order to face the growing demand of carbon neutral fuels, and to meet the ambitious target of decreasing global carbon emission by 50% set by the European Union by 2050.

In this context, ALGAESOL ("Sustainable aviation and shipping fuels from microalgae and direct solar BES technologies") is a publicly funded Horizon Europe project (GA No. 101147112 [1]), that aims to develop and evaluate innovative solutions for the sustainable conversion of sunlight into fuels. ALGAESOL will advance the current state-of-the-art by creating and consolidating new value chains for shipping and aviation biofuels based on micro-algae and direct solar renewable fuel technologies.

The core technologies developed in the ALGAESOL solar and algal pathways are a combination of electrochemical and microbial electrochemical technologies (METs), also known as bioelectrochemical systems (BES) when referring to the device used, which can be defined as "an electrochemical system in which electrochemically active microorganisms catalyze the anode and/or the cathode reaction" [2]. The main characteristics of BES are the presence of two electrodes concurring to a redox reaction, anode and cathode respectively, and the role of microorganisms relies in the catalysis of reactions happening at one or both electrodes. A microbial electrochemical technology is thus a hybrid approach that uses microorganisms to catalyse electrochemical reactions to convert waste carbon materials into bioenergy and bioproducts.

With the increasing interest on resource recovery and circular economy, METs appear like an appealing technology to produce valuable compounds, among all, biofuels [3]. A large variety of substrates can be used for (bio)electrosynthesis of value-added products. The choice of substrates for the (bio)electrochemical conversion of wastes into value-added chemicals has gradually been expanded to various wastewaters, solid wastes, and waste gas [4]. To achieve sustainable fuels production, waste gas and wastewater should be used as carbon source, thus mitigating emissions and enhancing circular economy. While the target fuels characteristics for the ALGAESOL project have been already set in Task T1.1 (and reported in the relative deliverable D1.1), the present deliverable D1.2 aims at (1) creating a database of waste gases and wastewaters ("Feedstock benchmark") to be used in the value-chains for ALGAESOL project and (2) defining the technical specifications of the technologies/processes involved to be developed throughout the project.

2. Feedstock benchmark

This section presents a selection of feedstocks to be potentially exploited as CO_2 source and/or process water in the ALGAESOL project streams. The section is divided into two subsections. The first subsection collects data about CO_2 sources (from industrial processes, combustion processes, and carbon capture and storage (CCS) sources), while the second part of the section focuses on process water and wastewaters characterization. The section is based on comprehensive literature research and emphasizes the essential features of the examined waste streams, with focus on the parameters that might affect the performances of the technologies involved.

2.1. CO_2 emissions composition from industrial, combustion and CCUS processes

Industrial processes are highly energy intensive and, currently, account for one-third of global energy use. Around 70% of this energy is currently supplied by fossil fuels, and CO_2 emissions from industry account for 40% of total CO_2 emissions worldwide. If emissions from the industrial sector remain unchecked, total emissions are projected to increase by 74–91% by 2050 (compared to 2007 levels) [5].

Carbon capture, utilization and storage (CCUS) is therefore a fundamental step in the synthesis of the new generation of sustainable fuels. For this reason, potential CO_2 sources to be utilized throughout the ALGAESOL project have been identified and collected: industrial processes (Table 2), combustion processes (Table 3), and CCUS processes (Table 4) have been included in the database generated.

Industrial gas emissions are characterized by high variability in terms of composition according to the process operated. The feedstock benchmark attempts to cover all relevant areas in the industrial sector:

- Energy;
- Manufacturing (i.e., Chemicals, Petroleum refining, Cement, Iron and Steel, Glass, Pulp&Paper, Food processing, Aluminium, etc.)
- Transportation;
- Agriculture and livestock.

It is important to highlight that the purity of CO_2 coming from fermentation industry is high enough to be directly reused [7]. Combustion processes from fuel engines (as their respective production process) often contain nitrous oxides (NOx), sulfur oxides (SOx) and hydrocarbons (HC), which might be harmful when applied in a biological process if not previously removed [6]. Aromatic compounds, volatile organic compounds (VOCs) and non-methane volatile organic compounds (NMVOCs) might also be detected in traces. Carbon monoxide (CO) is also often detected as byproduct of incomplete combustion. Combustion processes emissions from vehicles have been included in the database, even though their direct capture and utilization is not possible (or challenging) on-site.

CCUS involves the capture of CO_2, generally from large emission point sources like power plants or industrial facilities, that usually rely on fossil fuels or biomass as primary energy source and fuel. If not being used on-site, the captured CO_2 can be compressed and transported to be later used in a range of applications, or stored underground in deep geological formations (depleted oil and gas reservoirs, saline aquifers, etc.) [5]. Existing industrial and electricity plants can be retrofitted with CCUS, enabling large emitting source points, especially heavy industries like chemicals, steel, and cement, to reduce their emissions. Lastly, CO_2 removal from the atmosphere may help balance emissions that cannot be avoided or are technically challenging to reduce [7].

All core technologies presented in the ALGAESOL project rely on CO_2 as a carbon source: carefully selecting the most suitable feedstock is essential for the positive outcome of the process. This choice might affect also the site of future installation of the plant.

Table 2. CO_2 emitted from selected industrial processes

Source	CO_2 (%)	Other compunds	Reference
Petroleum refineries	3-18	O_2 (10%), NMVOCs, Benzene, NOx, SOx	[8], [9]
Iron and steel production	20-30	O_2 (11%), NOx, SOx	[9], [10]
Ammonia	~100		[9]
Hydrogen refineries	15-20		[3]
Cement and lime production	17.5 [14-33 %]	N_2 (65%), O_2 (10%) Ar (<1%) H_2O (6,5%)	[11], [12]
Chemical industry (Carbon Black process)	1-5	CH_4 (30-50%), CO, H_2	[13]
Power plants	10-15	SO_2, 1000-5000 ppm, NOx 100-500 ppm, O_2 4.6 %	[14]
Biogas (Landfill)	20-50	CH_4 (50-70%), H_2 (0-5%), Hydrogen sulfide (H_2S, 0.1%), O_2 (0-1%), N_2 (0-3%), CO (0 - 1%), Water H_2O (Saturation), Ammonia (NH_3, traces), Siloxanes (traces)	[15]
Biogas (Industrial waste)	30-50	CH_4 (50-80%), H_2 (0-2%), H_2S (0.7%), O_2 (0-1%), N_2 (0-1%), CO (0 - 1%), Water H_2O (Saturation), NH_3 (traces), Siloxanes (traces)	[15]
Biogas (Agricultural waste)	30-50	CH_4 (50-70%), H_2 (0-2%), H_2S (0.8%), O_2 (0-1%), N_2 (0-1%), CO (0 - 1%), Water H_2O (Saturation), NH_3 (traces), Siloxanes (traces)	[15]
Bioethanol	~100		[9]
Brewery industry	~100		[9]
Winery industry	~100		[9]

Table 3. CO_2 emitted from selected combustion processes.

Source	CO_2 (%)	Other compounds	Reference
Coal	12-15	SO_2 1000-5000 ppm, NOx 100-500 ppm, O_2 (4.6 %)	[9], [16]
Natural gas	3-17	CO, NOx, O_2 if not fully combusted	[9], [17]
Biodiesel	18	10% CO, 9999 ppm HC, 5000 ppm NOx	[6]
Fuel oil	3-8		[9]
Methanol	67.9 kg CO_2/GJ	low emissions of CO, HC, NOx, and particles. No SOx	[18]
Oxyfuel combustion process	74	H_2O (10.38%), N_2 (11.56%), O_2 (3.54%), SO_2 (0.33%), Ar: 0.40%	[19]
Biomass	3-8	1198-3072 ppm CO, 64-286 ppm NOx	[20]
Jet Fuel	50	0.1-0.7 g/kg fuel NMVOC, 0,01-0,03% SO2, 0,26-0,43% g/kg fuel CO, 6-20 g/kg fuel NOx, 0.01-0.2 g/kg fuel soot	[21]
Positive ignition vehicles	98 (g CO2/km	1.0 g/km CO, 0.10 g/km Total Hydrocarbons (HC), 0.068g/km Non-methane HC, 0.06 g/km NOx, 0.005g/km PM	Euro 6 regulation
Compression ignition vehicles	98 g CO2/km	0.50 g/km CO, 0.17 g/km HC and NOx, 0.08 g/km NOx, 0.005g/km PM	Euro 6 regulation

Table 4. CO_2 obtained from CCS processes

Source	CO_2 (%)	Impurities	Reference
Liquid CO_2 (LCO_2) from Northern Lights project	min 99.81%	H_2O < 30 ppm, O_2<10 ppm, SOx<10 ppm, NOx<1.5 ppm, H_2S <9 ppm, Amine <10 ppm, NH_3 <10 ppm, CH2O <20 ppm, CH_3CHO<20 ppm, Hg<0.0003 ppm, CO<100 ppm, H_2<50 ppm, Cd+Tl < 0.03 ppm, CH_4<100 ppm, N_2<50 ppm, Ar<100 ppm, CH_3OH <30 ppm, C_2H_5OH<1 ppm, VOC< 10 ppm, MEG <0.005 ppm, BTEX<0.5 ppm, C_2H_4<0.5 ppm, HCN<100 ppm, C_3+<1100 ppm, C_2H_6<75 ppm, solids <1µm	Northern Lights LCO_2 quality specifications [38]

2.2. Wastewater database

Water resources are currently under stress due to climate change in several parts of the world. Therefore, reducing the need of fresh water and chemicals becomes essential to minimize the impact of innovative technologies on resources essential for the human life [22]. Wastewater can be broadly divided in domestic wastewater, stormwater and industrial wastewater; both domestic and industrial wastewater can be profitable for resource recovery. While domestic wastewater quality might present more "standardized" characteristics, with little variation according to the area of collection, industrial wastewater quality varies widely according to the manufacturing process operated. Treating industrial wastewater offers the chance to recover resources, which can support continuing operations in the event (more and more diffused) of a drought. The efficient processing and repurposing of industrial wastewater is a significant challenge due to the complex and heterogenous properties of the waste-streams. Numerous inorganic and complex organic contaminants can be found in industrial wastewater, and there is an almost equal variety of possible physical, chemical, and biological treatment methods.

The importance of circularity for all matrixes utilized/modelled in the ALGAESOL project prompts the use of wastewaters for the synthesis of sustainable aviation and shipping fuels. Therefore, to ease the selection of the liquid matrix to be operated in the core technologies, a wastewater benchmark database has been prepared as complement of Task T1.2. UdG (with contribution of all partners) made available the shared database reporting the key parameters for wastewater characterization for each feedstock considered. For the completion of the database, both industrial process wastewaters and domestic wastewaters (also differentiating between phases of the treatment process) have been included in the table.

Several parameters have been considered in developing the database: pH, electric conductivity (EC), total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), ammonium (NH_4^+), total Kjeldahl nitrogen (TKN), total nitrogen (TN), total phosphorous (TP), chlorides, alkalinity (Alk). In the extended version of the database (to be published), also hardness, total organic carbon (TOC), nitrite, nitrate, phenols, oil and greases, and heavy metals have been reported.

Particular attention when selecting a real substrate for the use in BES should be dedicated to the presence of toxic components, pharmaceuticals and other compounds which might be harmful for the biomass. Another essential parameter to be considered, is the electrical conductivity. Conductivity is the ionic flow through a solution, municipal wastewater conductivity is relatively low, with values between 0.7 and 1.8 mS/cm, with the top value often considered as optimal [23]. Limitation in conductivity increases resistance and electrolyte Ohmic losses, reducing significantly the performance. In artificial wastewaters, conductivity is normally augmented by adding buffers typically in the range of 7.5–20 mS/cm, but industrial application of BESs cannot rely on the artificial supplementation of conductivity. At the same time, excessive salinity might also affect negatively the performances, due to possible toxicity effects on the biomass [24]. COD and biodegradability of the organic matter is also an important parameter to take into account in the selection of a wastewater. If CO_2 is the sole carbon source designated, carbon depleted wastewater should be chosen as main substrate, for example, municipal secondary settler effluent. Other relevant parameters, especially for on-site and in-situ applications, are temperature of the process water and of operation. BES reactors are usually operated in the mesophilic range, but experiments at lower (10°C) and higher (55°C) temperatures have also been conducted. Lastly, pH is relevant in function of the target reaction (and biomass involved) and for the preservation of the materials used for the construction.

Organic load rate, pH, conductivity and presence of toxic compounds affect heavily the performance of BES, but using process water presents also several advantages [23], [24], [25]:

- The use of real wastewater as a feed enhances development of a specialized biomass, which differs from the one detected with synthetic medium, and it might be more performing/resilient in the degradation of certain compounds (but specialized electroactive bacteria are still needed).

- Some real wastewater present higher buffer capacity than synthetic wastewater, limiting excessive and sudden fluctuations in the pH.

- The scalability of a reactor is the most important factor to go from laboratory scale to real industry applications, and the first (necessary) step is the validation of the technology with real matrixes.

Table 5 encloses an extract of the database generated, which will be published Open Source in its full version in the months following the submission of the present deliverable, to make it a valuable resource ready to use for other projects.

Table 5. Wastewater characteristics and composition (continues)

Type	pH	Conductivity [mS cm^{-1}]	TSS [mgTSS L^{-1}]	COD [mgO_2 L^{-1}]	BOD5 [mg O_2 L^{-1}]	Ammonium [mg N L^{-1}]	TKN [mgN L^{-1}]	TN [mgN L^{-1}]	TP [mgP L^{-1}]	Chlorides [mgCl L^{-1}]	Alk [mg HCO_3 L^{-1}]	Ref.
Brewery WW	3-12	0.4-3.7	200-3000	2000-32500	1200-3600	5-21.6		25-450	0.5-216	150-225	190-3173	[26]
Canning fish WW	6.1-7.2	4.8-58.0	100-6530	1147-59000	463-11000	3-1780	2080	21-4000	13-523	174-11500		[27]
Dairy WW	4-12	1.1-13.5	250-2700	650-3000	300-1400	10-20	10-140	10-20	10-132	50-500	257-657	[26]
Human Urine	8.7-9.1	31.5-41.7	-	900-45000		2390-8100			208-700	256-450	220-1070	[28]
Iron and steel WW	6.8		110-16000	2-35	<2	15				395		[29]
Kraft Pulp and Paper WW	3.9-7.3	0.6-5	36-2700	1333-10800	184-55500	0		4	0-2	987	83	[30]
Molasses processing industry WW	8.2-8.7	22.6	700-4400	4200-22800	1100-13200	35-620		80-28000	20-190		6000	[26]
Olive mill WW	4.6-6.6	2.0-11.3	18000-46011	7910-130000	14000-32100	17-750	168-1650	202-710	64-1820	21300	2039-3800	[30]
Palm oil mill effluent	3.4-5.6	0.19	5000-88258	39650-113000	11000-67000	4-80	672-1381	180-1400	180-368			[26]
Refinery WW	7.1-10	0.1	334-445	30-1180	201	13-49						[31]
Rice mill effluent	4.7-7.1	0.4-11.6	2-49140	400-19800	23-154	23-154	25-154	25-154	10-360	95-197	180-340	[26]
Slaughterhouse WW	8.0-8.5	0.1-3.0	10120-14225	990-40300	535-24900	650-735	1050-1200	1546-53516			11000	[26]
Soft drinks WW	4.9-11.8	0.1-3.7	28-2940	419-11717	34-1745	0-2		1-51	1-100	16-1218	75-4200	

Type	pH	Conductivity [mS cm^{-1}]	TSS [mgTSS L^{-1}]	COD [mgO$_2$ L^{-1}]	BOD5 [mg O$_2$ L^{-1}]	Ammonium [mg N L^{-1}]	TKN [mgN L^{-1}]	TN [mgN L^{-1}]	TP [mgP L^{-1}]	Chlorides [mgCl L^{-1}]	Alk [mg HCO$_3$ L^{-1}]	Ref.
Sugar industry WW	5.6-6.8	5.6-6.8	185-665	1046-6621	715-1680	30	10-42	49-53	0-5	133	1250-1760	[32]
Swine manure WW	7.0-8.0	3.4-18.2	10100-17700	800-4500		190-2600	700-3400	900-13400	46-722	915		[33]
Textile WW	8.7-11.8	8.8-11.8	233-401	267-1800	118					1.2		[34]
Winery WW	3.5-7.9	1.1-5.6	190-18000	340-49100	130-22418	5.2	48.3	10-415	2-280	0-39.9		[26]
Domestic WW	6-8	0.8	100-350	250-1000	110-400	12-50	20-85	20-85	4-15		50-200	[35]
Primary WW	7.5-8.1	0.7-0.9		60-120				15-65				[36]
Secondary WW				20-178	1-6	0-34		0-79				[37]

3. Technical specifications

As second part of the Task T1.2, a shared database between all partners for the collection of all the technical specifications for all technologies involved in the ALGAESOL project was developed. This document consists of an excel file, enclosing all relevant dimensional parameters, energy production/consumption, process flows and interactions of ALGAESOL production pathways, which will be updated all throughout the project (creating a shared database to keep track of all changes and conditions tested over time). The database has been created in collaboration with NORCE and SIMTECH, and it represents the guideline for modelling and sustainability analysis (LCA). Figure 1 shows the production pathways to be developed in WP2 (**direct solar technologies**) and WP3 (**microalgae-based pathway**) with the respective interactions; the corresponding technology names and numbers are reported in Table 6. Due to IP limitations in disclosing technical information about the processes, only a broad description of the technologies involved in each pathway and their interactions will be reported in the following paragraphs.

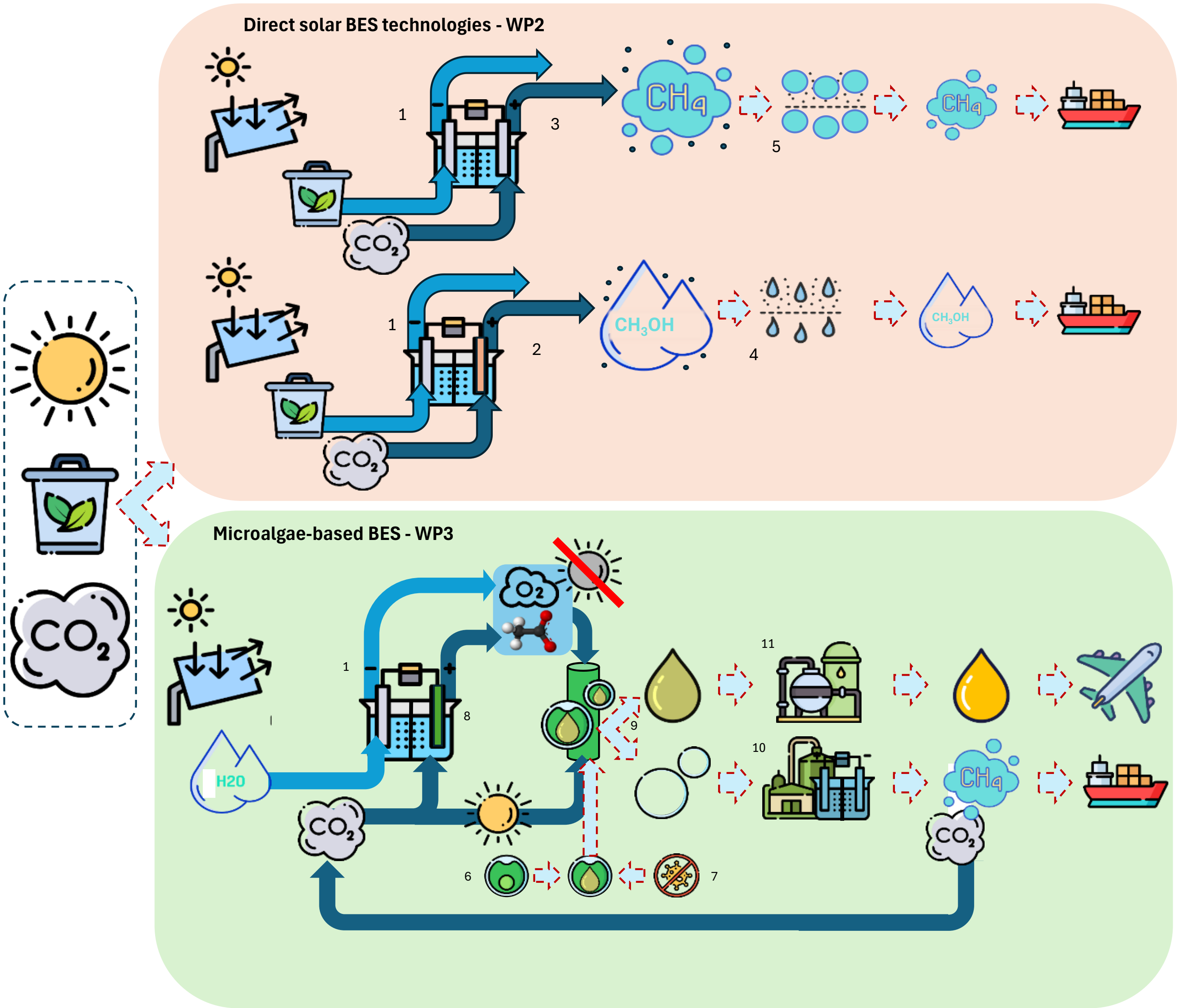

Figure 1: Renewable fuel production paths (Process Flows) evaluated in ALGAESOL.

Table 6: Technologies used / developed in ALGAESOL.

Legend	Technology	Abbreviation	Responsible partner
1	Photoanodes	P	LEITAT
2	EC-Methanol	EC/P-EC	LEITAT
3	BES-Methane	BE/P-BE	LEITAT
4	Methanol purification	pMeOH	LEITAT
5	Methane purification	pCH4	LEITAT
6	Microalgae cultivation	MA	NORCE
7	Microalgae pest control	MA-PC	DTI
8	BES-Microalgae	BE-MA/P-BE-MA	UdG
9	Lipid extraction	LE	LEITAT
10	Anaerobic digestion BES	AD-BES	LEITAT
11	Lipid processing	LP	SOCAR

Finally, figures 2 and 3 represent an example of technical specifications collection datasheet disseminated among the partners; one datasheet per technology has been generated according to Table 6. The datasheets have been used to collect all the relevant information and to further define the process flows conceptualized in the ALGAESOL project.

Technology name			
Version	v1	v2	v3
Month	MX -MY	MX -MY	MX -MY
Technology Design			
Description of the technology			
Reactor dimensions (if appliable – L x W x H, specify u.m.)			
Working volume (if appliable, estimate, L)			
Other relevant specifics (electrode surface, etc)			
Input and output flows			
Process input 1 (feedstock or byproduct from other process)			
Process input 2 (feedstock or byproduct from other process)			
Process input 3 (feedstock or byproduct from other process)			
Expected output 1 (product or input for other process)			
Expected output 2 (product or input for other process)			
Expected output 3 (product or input for other process)			
Specific energy in/out (specify u.m.)			
Electricity consumed (J or Wh per kg or L of product)			
Electricity produced (J or Wh)			
Heat consumed (J or Wh)			
Heat produced (J or Wh)			
Operational conditions applied			
Simulation streams			
Feedstock 1 for simulation			
Feedstock 2 for simulation			
Feedstock 3 for simulation			
Performance achieved			
Real output 1			
Real output 2			
Real output 3			
Deviations			

Technology scheme	

List of abbreviations

Figure 2. Example of technical specifications collection datasheet (overview).

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Processing equipment and material composition	Please, break it down to common materials such as borosilicate glass, stainless steel, carbon fiber etc.	Price [€/unit] provide the global cost of the equipment	Origin/Source please indicate manufacturer &/or provider
Equipment 1	Material 1, material 2, material 3...		
Equipment 2	Material 1, material 2, material 3...		
Equipment 3	Material 1, material 2, material 3...		
Input and output flows characterization	Amount consumed/produced [L or kg, specify]	Price [€/kg - €/L] - provide the cost per relevant unit (specify)	Origin/Source please indicate the synthesis or production process (if known), manufacturer name and location (if known), and/or provider
Input 1 - v1			
Input 2 - v1			
Input 3 - v1			
...			
Heat/energy flows characterization	Amount consumed/produced [kW/kg or J/kg, specify]	Price [€/Wh or €/J, specify]	Origin/Source please indicate if obtained from the grid, own generation (e.g. solar, excess heat from processes etc.) or other sources

Figure 3: Example of technical specifications collection datasheet: equipment and materials description, input and output flows characterization for modelling and LCA analysis.

3.1. Direct solar conversion

The direct solar conversion pathway uses photo(bio)electrochemical technologies aimed at renewable shipping fuel production, which consists of the activities to be carried out in WP2. Two main processes and relative products are enclosed in this WP. The first is photo-bioelectrochemical production of methane gas, and its purification process. This production pathway will be referred to as **Renewable Fuel Path 1** in D1.3 and it is shown in Figure 4. This pathway involves the following technologies:

- Photoanodes (P, 1)
- Electromethanogenesis BES (BE/P-BE, 3)
- Purification of methane (pCH4, 5)

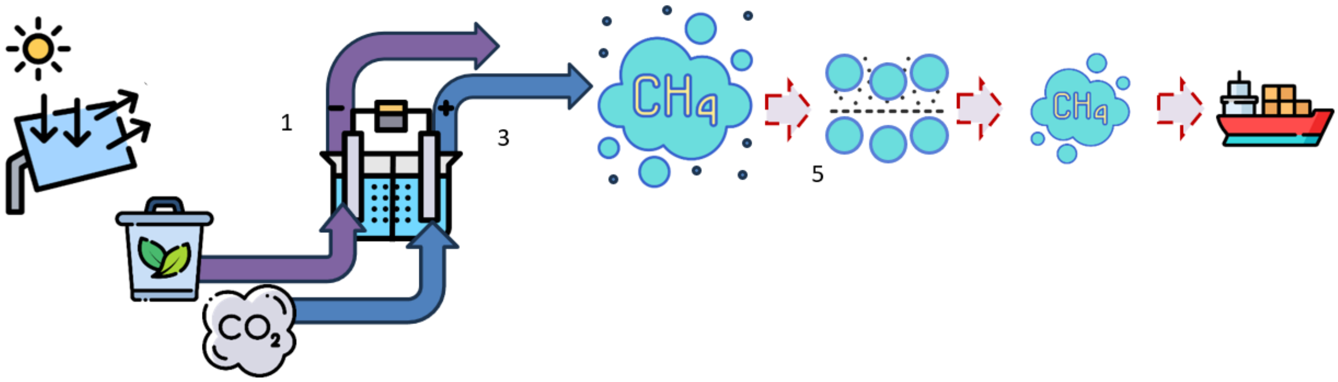

Figure 4: ALGAESOL photo-bio electrochemical production of methane for shipping.

The second pathway enclosed in WP2 is photo-electrochemical production of methanol, and its purification process. This production pathway will be referred to as **Renewable Fuel Path 2** in D1.3 and it is schematized in Figure 5. This pathway involves the following technologies:

- Photoanodes (P, 1)
- Electrochemical methanol production (EC/P-EC, 2)
- Methanol purification (pMeOH, 4)

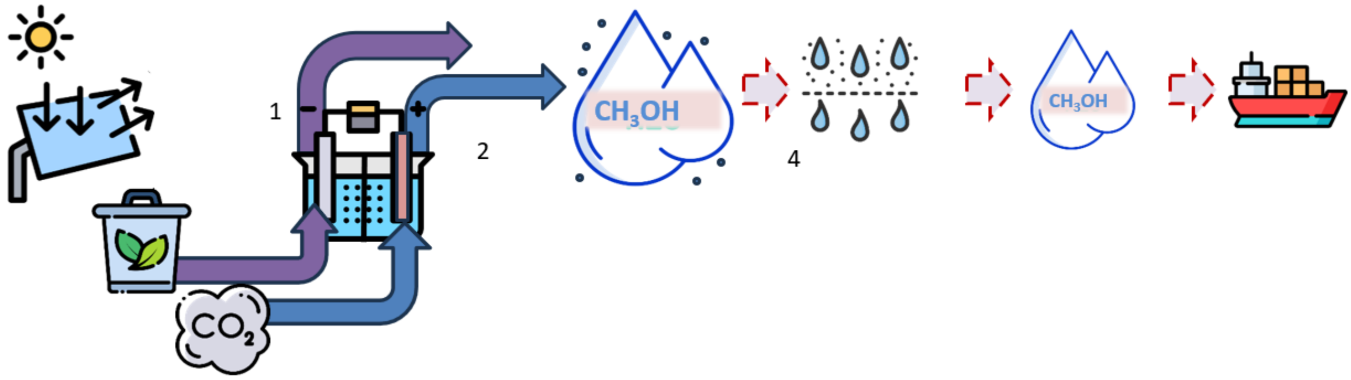

Figure 5: ALGAESOL photo-electrochemical production of methanol for shipping.

In Table 7, the essential technical specifications of the technologies involved in the direct solar conversion route are summarized.

Table 7: ALGAESOL direct solar conversion route overview and interaction.

Technology	P	BE	EM	pCH4	pEtOH
Description	Design and synthesis of engineered photoactive materials	Electro-methanogenesis unit, biocathode and abiotic anode for oxygen evolution	Development of an electrochemical cell, different cathode materials for CO_2 reduction to methanol, stable anode for OER	Gas permeation using membranes for methane purification	Combined distillation + pervaporation with membranes system for methanol purification
Process inputs	Electrolyte: 1M KOH for oxygen evolution reaction (OER), 1M KOH with organic matter for CO_2 production	Alkaline solution, synthetic WW, CO_2 Sunlight	Electrolyte, CO_2	Expected product from BES-Methane (BE/P-BE)	Expected product from EC-Methanol (EC/P-EC)
Process output	oxygen or CO_2 depending on the electrolyte	Oxygen, methane, treated wastewater	Oxygen, CH_3OH, CO, H_2, CH_4, HCOOH	Methane-rich stram, other gases	Methanol-rich stream, water rich stream
Interactions	BE, EM	P, pCH4	P, pEtOH	BE	EM
Versions	V1 material optimization V2 integration in BE (P-BE) and EM (P-EM) V3 Optimization (integrated)	V1 BE V2 P integration (P-BE) V3 P-BE with anodic organic matter	V1 EM V2 P integration (P-EM)	/	/

3.2. Microalgae-based conversion route

The microalgae-based conversion pathway uses photo- and bio electrochemical technologies aimed at renewable aviation and shipping fuel production, which consists of the activities to be carried out in WP2 and WP3. Two main processes and relative products are enclosed in this WP. The first is photo-bio electrochemical production of acetate, its coupling with microalgae and its microalgal lipid fraction separation and purification process aimed at aviation fuel production. This production pathway will be referred to as **Renewable Fuel Path 3** in D1.3 and it is schematized in Figure 6. This pathway involves the following technologies:

- Photoanodes (P, 1)
- Microalgae cultivation (MA, 6) and pest control strategies (MA-PC, 7)
- Bioelectrochemical acetate production (BE-MA/P-BE-MA, 8)
- Lipid extraction (LE, 9)
- Lipid processing (LP, 11)

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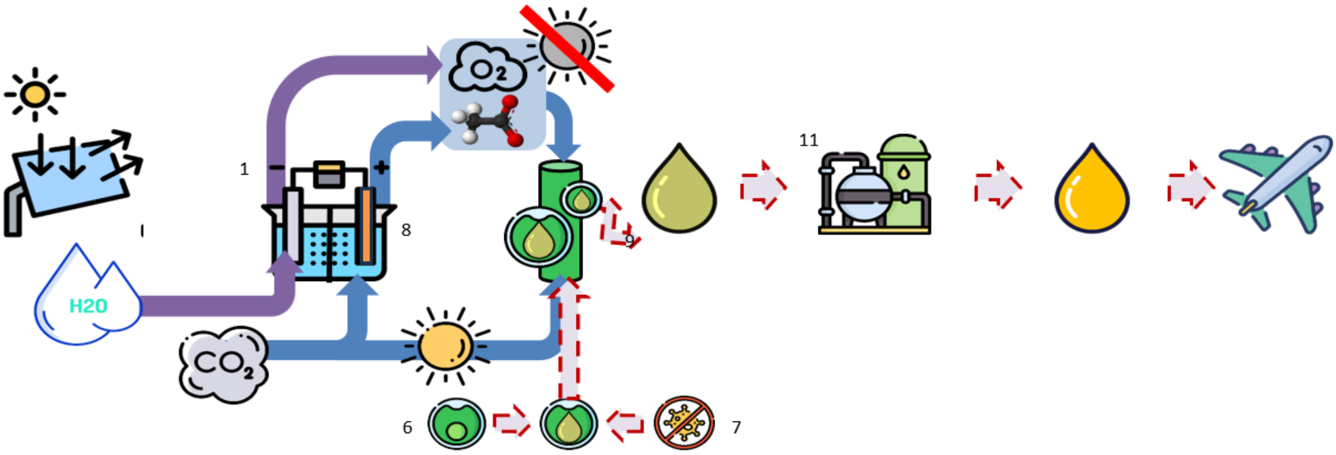

Figure 6: ALGAESOL Renewable Fuel Path 1, photo-bio electrochemical production of bio-oil for aviation.

The second sub-pathway is photo-bio electrochemical production of acetate, its coupling with microalgae, and operation of the residual microalgal starch in an AD-BES for the production of biogas, again to be operated as shipping fuel (Figure 7). This production pathway will be referred to as **Renewable Fuel Path 4** in D1.3. This pathway involves the following technologies:

- Photoanodes (P, 1)
- Microalgae cultivation (MA, 6) and pest control strategies (MA-PC, 7)
- Bioelectrochemical acetate production (BE-MA/P-BE-MA, 8)
- Anaerobic digestion BES (AD-BES, 10)
- Methane purification (pCH4, 5)

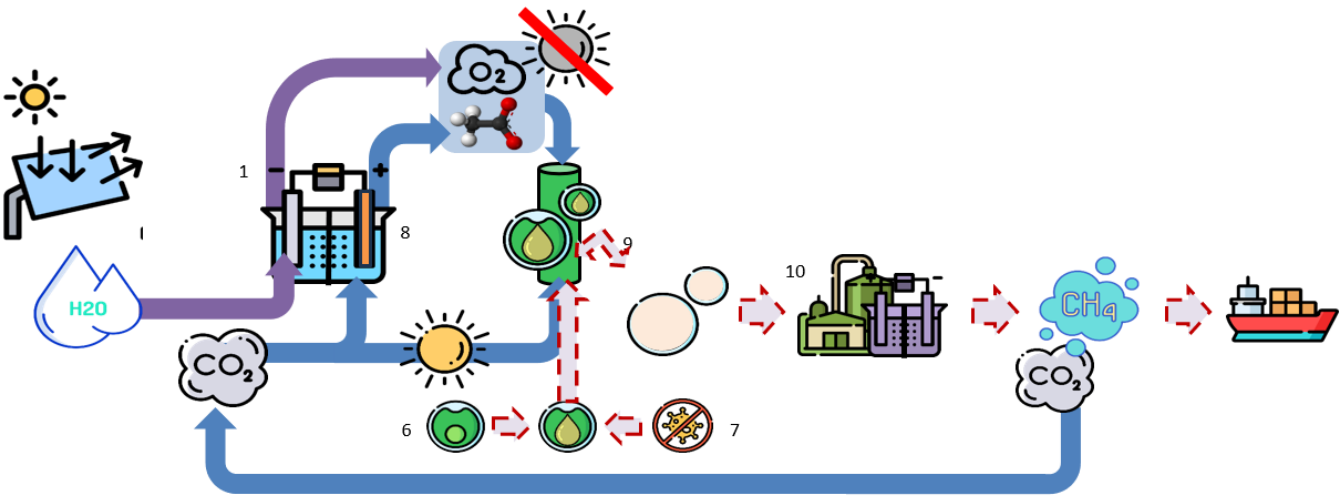

Figure 7: ALGAESOL combination of photo-bio electrochemical and anaerobic digestion BES for the production of shipping fuels.

In Table 8, the essential technical specifications of the technologies involved in the microalgae-based conversion route is summarized.

Table 7: ALGAESOL microalgae-based conversion route overview and interaction.

Technology	P	BE-MA	LE	LP	AD-BES
Description	Design and synthesis of engineered photoactive materials	Bioelectrochemical system for acetate production, combined with microalgae cultivation	Harvesting and concentration of microalgae, screening of extraction methods	Catalyst development and lipid conversion for sustainable aviation fuel production	Bioelectrochemically improved AD process
Process inputs	Electrolyte: 1M KOH for oxygen evolution reaction (OER), 1M KOH with organic matter for CO_2 production	CO_2, mineral medium, electricity	Microalgae solution, energy	Expected product from LE (lipid)	Expected product from LE (residual solid fraction)
Process output	oxygen or CO_2 depending on the electrolyte	Acetate, biomass, microalgae lipid-rich biomass	Water, liposoluble substances, residual solid fraction	SAF	CH_4, CO_2
Interactions	BE, EM	P, LE	LP, AD-BES	BE-MA	LE
Versions	V1 material optimization V2 integration in BE (P-BE) and EM (P-EM) V3 Optimization (integrated)	V1 BE-MA (only acetate production) V2 MA integration V3 P integration (P-BE)	V1 EM V2 P integration (P-EM)	V1 Catalyst development V2 Assessment of produced fuel	Expected upscaling (V1, V2, V3)

4. Conclusions

The report has identified the essential characteristics of the waste gas and wastewater to be potentially exploited to enhance circularity and carbon neutrality for sustainable shipping and aviation fuels. Furthermore, the information collected will be processed and made available to the researcher's community in compliance with the IP level of the present deliverable (Public). A technical specifications internal database, which will be used and updated throughout all the duration of the ALGAESOL has also been developed, although only essential information has been reported in the present deliverable due to IP limitations of some of the technologies involved.

5. Degree of progress

The report has successfully identified the essential characteristics of the feedstocks to be used and modelled in the framework of the technologies involved in the ALGAESOL project, creating a database for further uses in similar projects. Furthermore, baseline technical specifications of the technologies have been set, to provide the framework of development of the CO_2 recovery pathways into shipping and aviation biofuels that will be further developed in WP2 and WP3 of the ALGAESOL project. Due to the early delivery date (M6) compared to the full length of the project, and the sensitivity dissemination level of some of the technologies/processes involved, it was not possible to include detailed description of all the technical components involved. The deliverable has been completed on schedule, meeting the main objective of assessing a framework and structure for further modelling and to provide a more detailed pathway for aviation and shipping sustainable fuels production, enlightening the key processes and intersections between the ALGAESOL technologies. The next steps will involve the full development and optimisation of the technologies involved in WP2 and WP3, all improvements and actualization will be included in the technical specifications internal database generated for the preparation of this deliverable.

6. Dissemination level

The dissemination of information related to the ALGAESOL project deliverable 1.2 is categorized as Public, with no restrictions under the conditions of the Grant Agreement. While the feedstocks database is fully public, and a version to be published in Open Research Europe (https://open-research-europe.ec.europa.eu/) is currently under preparation, the technical specifications of the technologies involved in the project are subject to a sensitive dissemination level for further exploitation. For this reason, the detailed technical specifications information disclosed in this report are limited, and extensive attention has been posed on providing a consistent framework and an internal database to guide the connections and pathways presented in the ALGAESOL project. Careful consideration will be given to the timing and manner of dissemination of such information, to safeguard sensitive data while maintaining compliance with all relevant regulations and agreements.

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