POLITECNICO DI MILANO

Energy and Emissions in Transportation Systems

Prof. Guandalini

Project Work

AN ANALYSIS ON DME-FUELLED GARBAGE TRUCKS

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Academic Year 2021 – 2022

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1. SUMMARY

In the following study we will consider the implementation of a dimethyl ether (DME) synthesis plant in the region of Northern Italy.

We will perform our study considering a circular economy framework, as suggested by some studies like (Econward, 2020).

We will consider first a conventional DME-synthesis process and we will perform an analysis both from the technical and the economic point of view. This analysis will take into account different factors, including the logistic process of garbage collection and the Well-to-Wheel analysis of the greenhouse gases emissions.

At the end of the process, we will compare the results obtained with those obtained by (Guandalini & Romano, 2020) and (Econward, 2020) in the FLEDGED project analysis. Furthermore, we will point out some of the main criticalities of this process and propose some possible solutions and improvements.

2. INTRODUCTION

2.1. An overview of DME in heavy duty sector

Dimethyl Ether (DME) is an organic compound with the chemical formula CH3OCH3. For decades it has been used in a variety of products and applications such as propellants in aerosol cans, cooking fuels, solvents and medical treatments due to its lack of odour and toxicity and its ability to be absorbed into the troposphere. However, it can also be made into a viable alternative for diesel fuel, most notably for use in heavy haul transport vehicles.

Unlike conventional diesel, which is produced from non-renewable crude oil, DME can be produced anywhere using renewable products like municipal solid waste and biomass such as forest products and animal waste. This provides a great deal of flexibility for production since facilities do not need to be located near sources of crude oil but can be setup any place where bio-based feedstocks can be found or produced (Patten & McWha, 2015).

2.2. State of the art on DME synthesis: FLEDGED Project

As stated in the final report of the project (Guandalini & Romano, 2020): the FLEDGED project developed a process for the synthesis of DME from second generation biomass gasification, through two innovative processes: Sorption-Enhanced Gasification (SEG) and Sorption Enhanced DME Synthesis reactor (SEDMES).

After the process of gasification and cleaning, syngas is fed to the SEDMES unit, which is a direct DME synthesis process occurring on a bed of catalyst and water sorbent. By coupling SEG and SEDMES units, the resulting overall FLEDGED process results to be highly intensified. As can be seen in Figure 2.2-1 (Guandalini & Romano, 2020), the FLEDGED synthesis process requires less steps and components with respect to the conventional DME synthesis process from biomass.

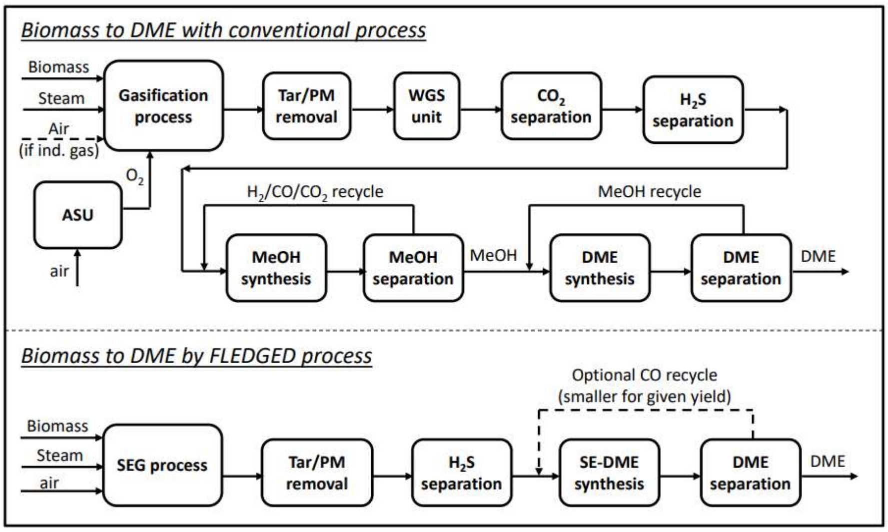

Figure 2.2-1: FLEDGED process vs. conventional process

FLEDGED has three main points that contribute to its flexibility:

1) Fuel flexibility
2) Operational flexibility
3) Retrofitting to biomass conversion process with CO2 capture and storage

2.3. Examples of projects

FLEDGED project presents three alternatives for a DME synthesis plant:

1) F1 – baseline case: usage of conventional technologies for the synthesis of DME starting from biomass, integrated with the SEG (sorption enhanced gasification) and SEDMES process units
2) F2 – CCS case: sorbent regeneration is performed in the SEG unit, using pure oxygen. This allows to generate a CO_2 enriched stream that can be either stored or used later. The origin of this CO_2 is biogenic, therefore the process has a negative emission balance.
3) F3 – Hydrogen case: DME yield is increased by adding an electrolysis unit that provides hydrogen when the renewable electricity price is sufficiently low. Within this process, the amount of CO_2 separated in SEG stage is reduced.

In Figure 2.3-1 (Guandalini & Romano, 2020) the different configurations of the plant can be seen:

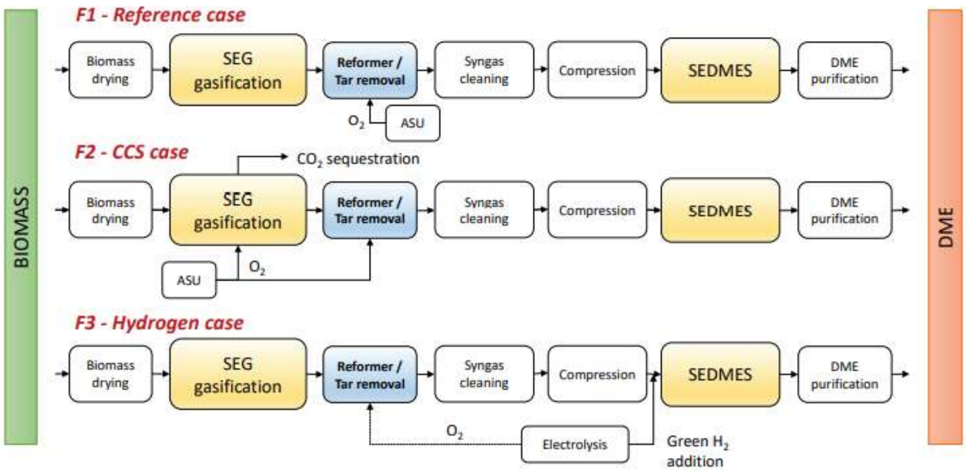

Figure 2.3-1: different configurations of the plant according to F1, F2 and F3 case

In the study, the economic efficiency for the three cases has been evaluated. In our analysis we are going analyse a conventional DME-synthetising plant, performing a sensitivity analysis in the last paragraph of the economic evaluation to show some possible improvements for the plant efficiency if we decided to use F1 or F3 alternative.

The baseline FLEDGED plant F1 has an overall fuel efficiency of 58.5%, mainly deriving from the gasification efficiency of 74.1% and the SEDMES fuel efficiency of 75.2%. When operated in the enhanced mode (case F3), hydrogen addition increases overall fuel efficiency up to 93.3% (referred to biomass input only, 65.7% considering the hydrogen energy input).

Both technical and economic performance of the plant are strongly influenced by the efficiency of SEG and SEDMES innovative technologies.

In the final report of the project, some possible improvements are suggested with respect to different sections of the analysis:

- Reduction of the steam-to-carbon ratio for the SEG section, with the possibility to adopt a two-stage gasification process
- Reduction of the capital expenditure acting on two fronts: the materials side, with the adoption of catalyst active at lower temperature, and the design of the reactors and SEDMES cycle side, by improving the heat management to allow for a larger reactor

3. CASE STUDY DESCRIPTION

3.1. The case study

In this specific analysis, we will consider a plant based in northern Italy organised according to circular economy framework that can be seen in Figure 3.1-1.

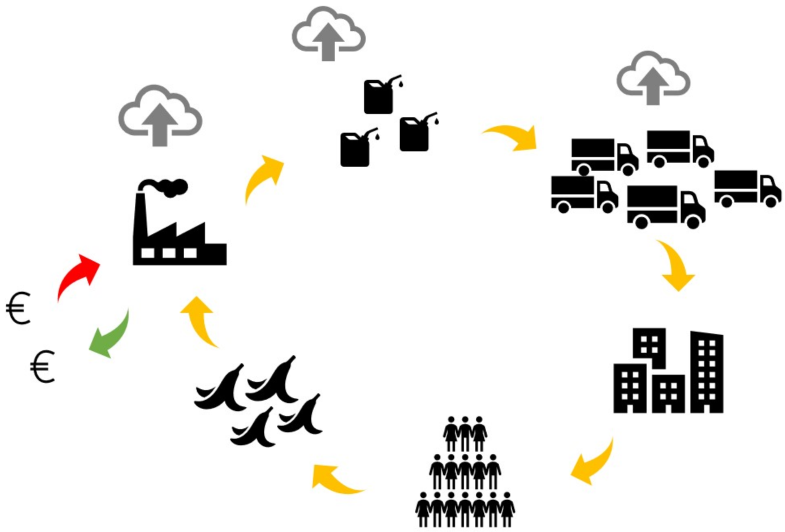

Figure 3.1-1: a scheme of the circular framework according to which the analysis is performed

Although we are going to analyse a conventional plant, we started our computations assuming the data provided by (Econward, 2020) regarding the FLEDGED project to synthetise DME. From these data, we can estimate the dimensions and yield of biomass to feed the plant with, as well as the efficiency of the process.

Once these data are specified, it is possible to compute the amount of DME produced by the plant in during the operative phase, assuming a constant production 24 hours a day and 14 days of shutdown to allow maintenance operations.

From the daily DME produced, it is possible to estimate the amount of refuellable trucks supposing to use the IVECO EUROCARGO E6, properly adapted to run on DME instead of diesel. These trucks will perform the collection process of municipal solid waste (MSW) that will be then separated into biomass and fed to the plant. From the amount of MSW needed to run the plant, an estimation of the number of people needed to constantly run the plant will be made.

We will perform an economic analysis of the plant and of the available incentives on the market to estimate the costs of an eventual implementation of this system, and in conclusion we will conduct a Well-to-Wheel analysis to show the difference of GHG emissions and other pollutants between DME and Diesel.

3.2. Study goals

The goals of this study are described in the following sections:

1) **Chapter 4:** Sizing the plant and performing an analysis on the chemical reactions and processes. Analysing the actual diesel truck situation, performing the switch to DME and providing two different alternatives: one in which the autonomy of trucks is reduced due to lower energy density of DME with respect to diesel, and another one where autonomy of trucks is the same as the one of diesel today and changes are apported to the trucks' tanks. Conducting a simulation of the logistic process. Performing a Well-To-Wheel analysis of the whole circular process.
2) **Chapter 5:** Executing an economic analysis that involves the whole plant construction, as well as the trucks' switch and the possible price reduction that comes from existing incentives. Simulating a

sensitivity analysis in which the main problems of the process are addressed and some parameters are varied (scenarios F1 and F3 proposed by FLEDGED) to show how further development of the technology can improve the performances of the plant.

3) **Chapter 6:** conclusions and final considerations.

4. TECHNICAL EVALUATION

4.1. Scheme of the plant

During this project, the data provided by (Econward, 2020) were used. The scheme can be seen in Figure 4.1-1 (Econward, 2020), while the main characteristics of the plant are reported in Table 1.

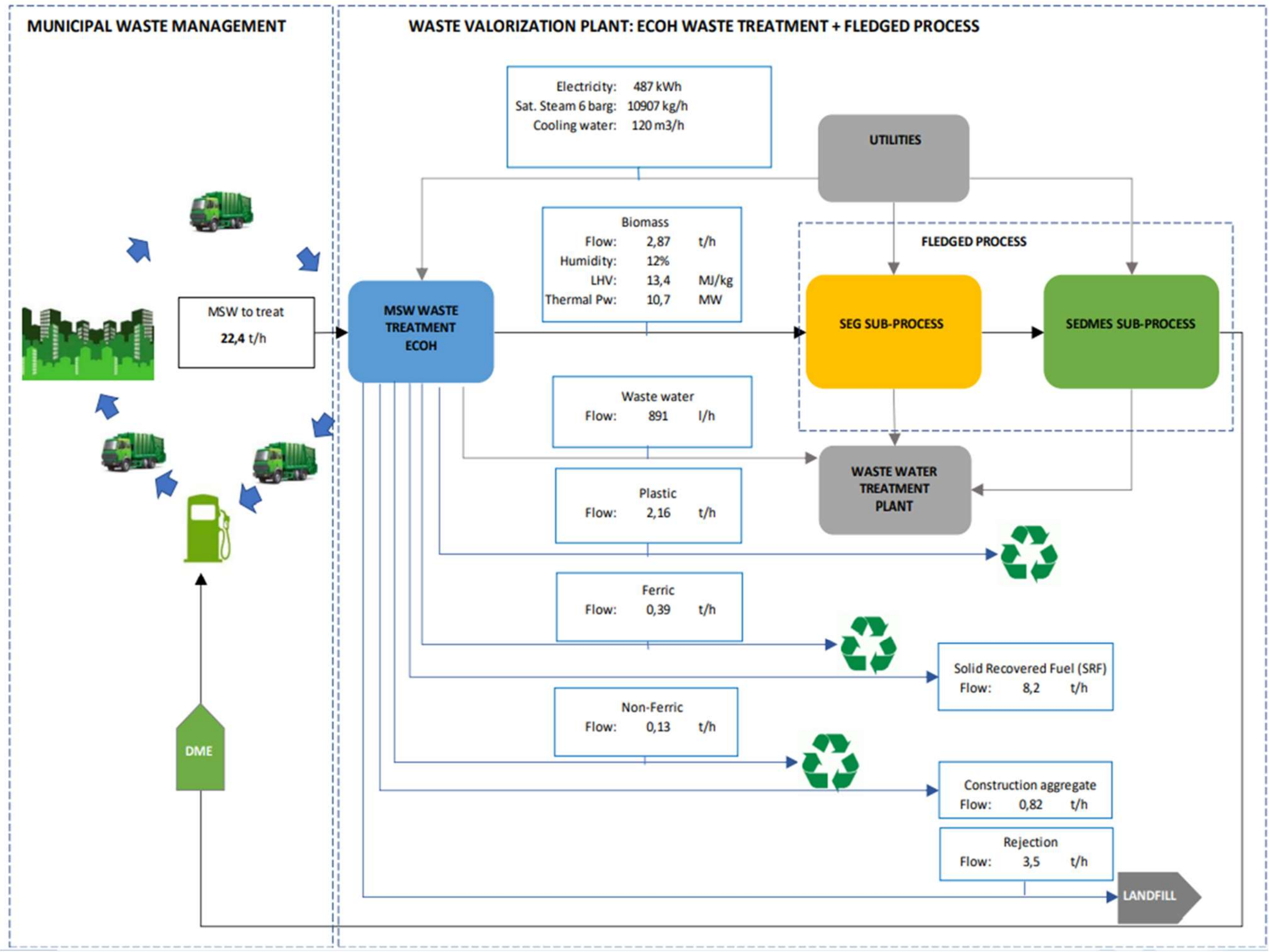

Figure 4.1-1: scheme of the plant for DME synthesis

Table 1: main characteristics of the plan as reported by Econward Study

FLOW RATE OF WASTE	22.4	t/h
BIOMASS PRODUCED	2.87	t/h
BIOMASS LHV	13.4	MJ/kg
EFFICIENCY	60	%
STEAM FOR GASIFICATION	0.35	kgH2O/kgBiomass
OXYGEN FOR GASIFICATION	0.3	kgO2/kgBiomass
CGE GASIFICATION	74	%
SEDMES EFFICIENCY	75	%

4.2. Plant sizing

Starting from the previous data, we calculated the equivalent amount of DME needed to provide the same energy provided by 1L of Diesel:

$$l_{DME} = \frac{1l_{diesel} * LHV_{diesel} * \rho_{diesel}}{LHV_{DME} * \rho_{DME}}$$

After this, we proceed to compute the litres of DME produced per ton of biomass, as follows:

$$E_{syngas} = \frac{E_{diesel(1l)}}{\eta_{synthesis}}$$

$$E_{biomass} = \frac{E_{syngas}}{CGE_{gasification}}$$

$$M_{biomass} = \frac{E_{biomass}}{LHV_{biomass}}$$

$$y_{DME} = \frac{l_{DME}}{M_{biomass}[t]}$$

The results are reported in Table 2.

Table 2: results of first sizing

$\boldsymbol{l_{DME}}$	1.86	l
$\boldsymbol{E_{syngas}}$	42.9	MJ
$\boldsymbol{E_{biomass}}$	71.5	MJ
$\boldsymbol{M_{biomass}}$	5.34	kg
$\boldsymbol{y_{DME}}$	347.82	$l/t_{biomass}$

From here, we can perform a series of different calculations.

4.2.1. Chemical reactions involved

DME can be produced from syngas as a mixture of CO, CO2 and H2. We based the following steps and calculations on (Guandalini, Poluzzi, & Romano, 2018).

The plant is divided in two reactors: the first one is a conventional reactor in which the following reactions are involved

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

$$CO + 2H_2 \leftrightarrow CH_3OH$$

$$2CH_3OH \leftrightarrow CH_3OCH_3 + H_2O$$

After the first reactor, in FLEDGED project there is a second stage in which a fraction of water is removed before SEDMES and SEDMES products are cooled for heat recovery and DME separation. We will analyse more in detail the costs and benefits associated with this alternative in the economic analysis.

Analysing more in detail the amount of CO2, H2 and DME produced:

$$\eta_{synthesis} = 0.78$$

$$\chi_{H2} = 3\frac{mol_{H2}}{mol_{DME}}$$

$$N_{DME} = \frac{M_{DME}}{M_{w,DME}}$$

$$N_{H2} = N_{DME} * \frac{\chi_{H2}}{\eta_{synthesi}}$$

$$\chi_{CO2} = 1 \frac{mol_{CO2}}{mol_{DME}}$$

$$N_{CO2} = N_{DME} * \frac{\chi_{CO2}}{\eta_{syngas}}$$

$$M_{CO2} = N_{CO} \quad * M_{w,CO2}$$

$$M_{H2} = N_{H2} * M_{w,H2}$$

Results are reported in Table 3.

Table 3: results from chemical reactions

$\boldsymbol{M_{w,DME}}$	46.07	Kg/kmol
$\boldsymbol{M_{w,CO2}}$	44.01	Kg/kmol
$\boldsymbol{M_{w,H2}}$	2.01	Kg/kmol
$\boldsymbol{N_{DME}}$	0.027	Kmol
$\boldsymbol{N_{H2}}$	0.101	Kmol
$\boldsymbol{N_{CO2}}$	0.033	Kmol
$\boldsymbol{M_{CO2}}$	1.486	Kg
$\boldsymbol{M_{H2}}$	0.203	Kg

4.2.2. Estimation of the municipality dimensions

In the optic of circular economy, once the dimensions of the plant are chosen it is possible to evaluate the number of MSW needed to feed the plant daily.

We assume for Northern Italy an average production of 90 kg of MSW per citizen per year. We compute the amount of DME produced per hour, considering the yield of DME and the biomass fed per hour (Table 1) to the plant. We can now compute the amount of DME produced per day, assuming the plant works 24 hours a day.

$$DME_{day} = 23'958 \frac{l}{day}$$

Knowing the flow rate of MSW from which the biomass is extracted (Table 1), we can compute the amount of MSW needed and from there we obtain the number of citizens needed to produce that amount. We obtain 2.18 million people.

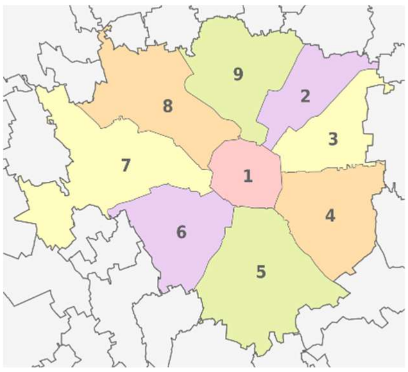

Figure 4.2-1: Milan municipalty, with an overall amount of 3.26 million citizens

This number corresponds to the most part of the municipality of Milan (Figure 4.2-1), or the sole city of Milan plus other cities like Brescia and Bergamo. We chose to analyse first the case in which the municipality of Milan is the sole provider of MSW to the plant.

4.2.3. Amount of refillable trucks

We decided to perform the collection process using the IVECO EUROCARGO E6 truck (Figure 4.2-2), switching an amount to be determined from diesel propulsion to DME propulsion. The technical specifics of the truck are reported in Table 4.

Figure 4.2-2: IVECO EUROCARGO E6

Table 4: IVECO EUROCARGO E6 specifics

POWER	137	KW
BRAKE HORSE POWER	183,58	HP
TORQUE	680	Nm
TANK CAPACITY	120	l
AVERAGE FUEL CONSUMPTION	15,39	l/100km
AVERAGE FUEL CONSUMPTION	6,498	km/l
DIESEL FUEL DENSITY	830	g/l

Knowing the ratio between the energy quantity of DME and Diesel, it is possible to calculate the amount of DME needed to provide the same autonomy to the trucks:

$$E_{needed} = E_{equiv} * C_{tank}$$

$$C_{tank,new} = \frac{M_{DME,needed}}{\rho_{DME}}$$

$$tank_{ratio} = \frac{C_{tank,new}}{C_{tank}}$$

This calculation bears the hypothesis that it is feasible to almost double the tank of the trucks, maintaining the same autonomy. Should this operation not be feasible, the new autonomy is calculated keeping the tank of 120 l of capacity. Results are reported in Table 5.

Table 5: results of the truck switch

$\boldsymbol{E_{equiv}}$	34.34	MJ
$\boldsymbol{E_{needed}}$	4’120.32	MJ
$\boldsymbol{C_{tank,new}}$	222.82	l
$\boldsymbol{tank_{ratio}}$	1.86	
$\boldsymbol{autonomy}$	778.8	Km
$\boldsymbol{autonomy_{new}}$	419.4	Km

From the amount of DME produced by the plant in one day (Par. 4.2.2), it is possible to compute how many trucks we can refill per day in both scenarios:

$$n_{trucks,new\ tank} = 107\frac{trucks}{day}$$

$$n_{trucks,old\ tank} = 199\frac{trucks}{day}$$

As the following paragraph will demonstrate, the collection process is not limited by the tank size. This means that even in the small tank case scenario, we could still be able to perform the collection of garbage and therefore sell on the market a fraction of the produced DME with a consequent cash inlet.

4.3. Collection Process

The aim of the collection step is to identify both the number of trucks needed in order to complete the service and the variables that could be limiting it, accounting for the following assumptions:

1- trucks run at 3,2 km/h during the collection and at 50 km/h during the travel phase from/to the plant
2- during the collection it is not reasonable to expect the trucks to run just once a road due to the complexity of the network. In order to overcome this limit of the model, we chose to consider an inefficiency parameter of 1.5 that amplifies the total number of km in the intra-city run. This doesn’t apply to the extra-city run from/to the plant
3- a total mass of 2,5 tons has been considered to be carriable by a single truck.
4- The plant has been located in the coordinates:

   45°23'45.1"N
   9°11'45.8"E

5- two reasonable work shifts have been considered: one is a 2x8 hours shift and the other one is a simple 8 hours shift per truck
6- Milan has been split in the municipalities (Figure 4.2-1), and to each has been assigned the related data about inhabitants and number of km of the road. Data used in this assumption has been extracted from ISTAT
7- trucks run on tanks that present the same energy content of diesel equivalents, thus an almost double-sized tank is needed

The analysis is structured based on two starting parameters: the amount of km that a truck has to run on average in a specific zone of Milan and the amount of mass that a truck has to collect in a single run.

Following the DME production based on the total collectable mass in Milan, a number of 107 DME-fuelled trucks with a full tank has been assumed. Said trucks have been repartitioned in all the zones based on the two previously discussed variables: as an example, the Municipalities 6 and 8 of Milan weight respectively as

0,088 and 0,164 on km basis and as 0,108 and 0,135 on mass basis, showing how the two variables act on and affect differently the problem (Table 6).

Table 6: truck allocation based on municipality

MUNICIPALITY	WEIGHT KM BASIS	WEIGHT MASS BASIS	REAL KM FOR COMPUTATION	MASS COLLECTED	ALLOCATED TRUCKS ON KM BASIS	ALLOCATED TRUCKS ON MASS BASIS
1	0.109	0.070	797	24295	12	8
2	0.073	0.116	535	39967	8	12
3	0.094	0.103	687	35533	10	11
4	0.120	0.115	876	39834	13	12
5	0.089	0.090	655	3109	10	10
6	0.088	0.108	643	37304	9	12
7	0.116	0.125	847	43265	12	13
8	0.164	0.135	1203	46446	18	15
9	0.143	0.134	1048	46300	15	14

This leads to assigning, coherently with above example, 9 and 18 trucks on km basis and 12 and 15 on mass basis.

Applying same procedure for all trucks for both variables and implementing the number of km run by trucks for the from/to plant travels we obtain the average number of km run by each truck per each zone. This an average of almost 90 km/day/truck for both variables. From this we can confidently say that the number of km that a truck can run with reference to the tank capacity is not a limiting factor.

It is now possible to compute the number of km that a truck can run on average before filling the garbage tank, which results in almost 50km. Considering the total number of km per zone and the number of km that a truck can run before being full, we can extract the number of trucks needed for collecting all the garbage on mass basis, which results in 137 trucks (in table 7 titled ‘N. Of trucks for mass collection’) . As for now, this seems to be the limiting variable.

Further expanding the analysis, we obtain that a single truck would need, depending on the zone of course, approximatively 255 hours in order to cover the full extent of a single zone.

Although not relevant, this information is useful in order to compute the number of hours that the previously allocated trucks take in order to cover all the assigned zones. Depending on the basis for allocation, the numbers change drastically and may even reach beyond 24 hours, making it clear that a support coming from diesel trucks is inevitable. It is to be underlined that this line of thought is based on full consumption of fuel tanks each day.

In order to simulate a more realistic scenario, the number of trucks that should be allocated on both basis in order to fully complete the service has been computed, considering work shifts of 8 hours. By doing this, a strong dependence on the composition of shifts has been introduced.

If a single work routine of 8 hours per truck is introduced the total number of trucks is of 294 (187 diesel), whereas with a 2x8 hours shift in the same day the number drops drastically to 148 (41 diesel), suggesting an almost fully DME based collection process feasibility.

From here, we can re-evaluate the actual number of feedable trucks in a day: with the previous number of 107 trucks/day and the average km/day of 90 as said before, there is no need to consider strictly full tanks and we can better arrange the fuel in a better way, completely fuelling the following disposition:

Table 7: final truck allocation depending on the municipality

MUNICIPALITY	N. OF TRUCKS FOR MASS COLLECTION	N. OF TRUCKS PER WORK SHIFT	FINAL NUMBER OF TRUCKS	AVG OF KM RUN BY EACH TRUCK	CONSUMPTION OF DME IN ONE DAY (l)
1	10	16	16	86.25	394.84
2	16	11	16	105.52	332.08
3	15	14	15	118.68	475.36
4	16	18	18	80.68	415.50
5	13	14	14	75.62	302.91
6	15	13	15	82.73	307.70
7	18	17	18	105.47	512.97
8	19	24	24	97.32	668.29
9	19	21	21	82.32	494.64

The column titled ‘Final number of trucks’ shows the final organization of the trucks in the various zones and takes into account the previously discussed variables, combining the number of trucks in order to respect all the limits imposed by them. As an example the number of trucks needed in terms of time for zone 2 would be of 11, but this number would not allow for a complete collection of garbage due to the size of the garbage tank.

With an average consumption of 3.50 km/l of DME it is possible to fuel the 157 trucks twice in the same day, with an average of travelled km/day of 90, using just 2707 kg of DME/day. Of the 16052 kg/day of DME that we are producing, only 2707 kg/day are actually needed in order to abundantly fuel the collection process, while circa 13344 kg/day are available to be sold or stored.

We are not taking into account any eventual extra-work usage of fuel, but since a relevant part of the km travelled by the trucks is composed by the from/to plant travels, which present a much lower consumption/km, the whole computation is strongly on the safe side.

In conclusion, no criticalities have been found in the feasibility of the collection process and, under the previously specified assumptions, the collection could provide fuel for both the operations and economic profit.

4.4. Well to Wheel emission analysis

In this section of the report, we will pursue the objectives of estimating the Greenhouse Gases (GHG) emitted from the start of production of the fuel till the burning phase in the engines, where GHG is released into the atmosphere.

The results will be compared between the conventional fuel used today, Diesel, against the potential fuel of the future, DME. As stated in Par. 4.2.3 we performed the analysis using the IVECO EUROCARGO E6, whose datasheet is reported in Table 4.

4.4.1. Diesel WtW emission analysis

Before computing the data, the pathway of the fuel was established.

Figure 4.4-1 shows the production chain of diesel extraction during the refining stage. The extracted diesel fuel chosen for this study complies with the normal European quality of cetane number 55.

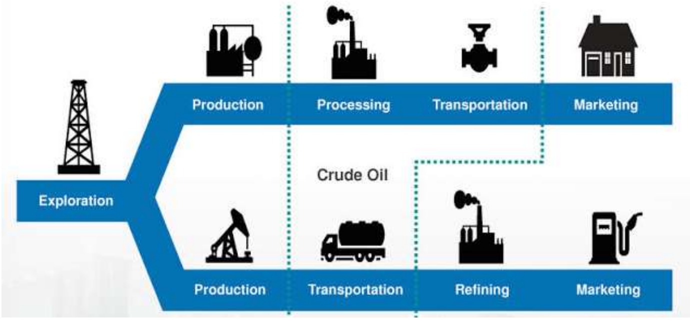

Figure 4.4-1: a scheme of Diesel production chain

Considering the study to be conducted in a European market, we consider the fuel production plants and pipelines to be established in Norway as shown in Figure 4.4-2. The production chain of fuel is split into 4 distinct phases:

- Production and Conditioning at source
- Transportation to market
- Transformation near market
- Distribution of the fuel.

CO_2 emissions for all the phases of fuel production are estimated.

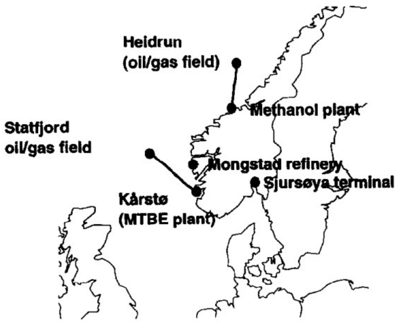

Figure 4.4-2: Diesel extraction sites

Elements like oil drilling and construction of offshore production platforms and pipelines are defined outside this study. The study compares the CO_2 emissions in the air and the complete Well-to-tank results of Diesel are given in Figure 4.4-3.

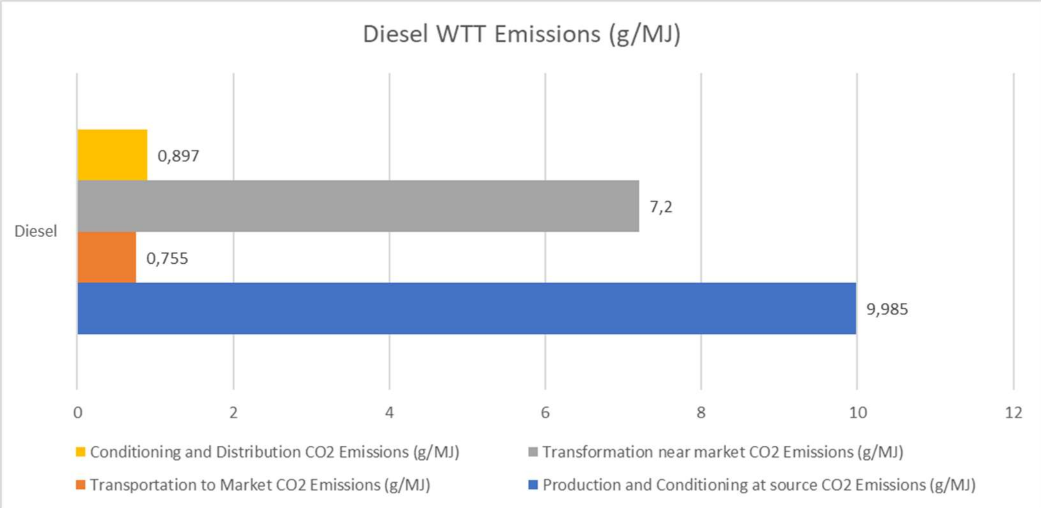

Figure 4.4-3: WTT emissions for Diesel

After computing the Well-to-Tank emissions, our objective is to complete the WtW assessment by computing the remaining Tank-to-Wheel emissions that are released into the atmosphere till the end of life of the vehicle. Considering the specifications of IVECO EUROCARGO E6 mentioned above, the following GHG were estimated (Figure 4.4-4).

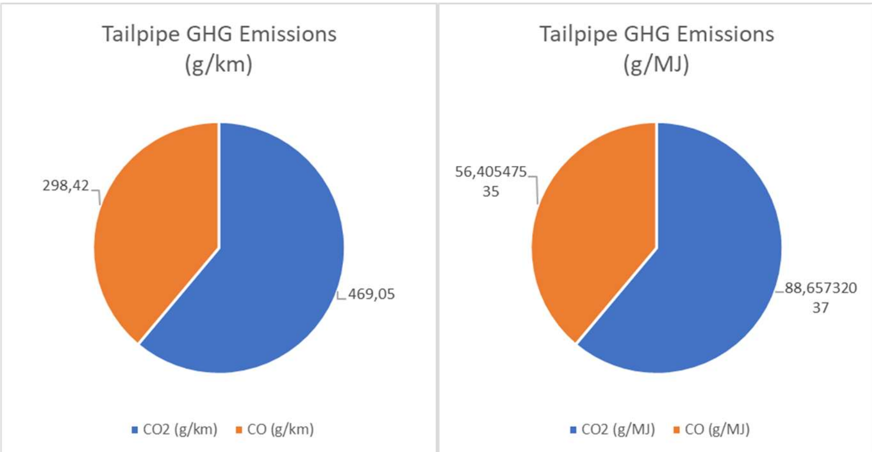

Figure 4.4-4: estimation of the GHG and CO emissions of Diesel in the TTW phase

4.4.2. DME WtW emission analysis

As discussed in the previous paragraphs, the production chain of DME is different than the one of conventional fuels.

The carbon emissions of the production plant are not considered, since we are storing already existing CO2 into DME until the burning phase, meaning the plant is Carbon Neutral.

The Well-to-Wheel analysis approach for this synthetic fuel considers only the electricity exploited in the gasification phase of DME synthesis. Electricity production chain for the Well-to-Tank Analysis of DME is depicted below in Figure 4.4-5.

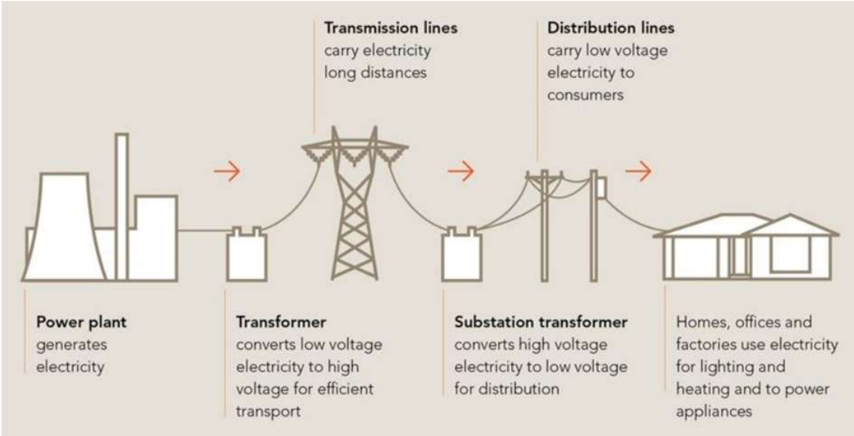

Figure 4.4-5: production chain of electricity

Considering European Mix of Power generation, the source of power varies between Natural gas, Coal, Oil and Renewable Energy. The current weight of power generation of electricity specifically in Italy is shown below in Figure 4.4-6 (data collected from International Energy Agency).

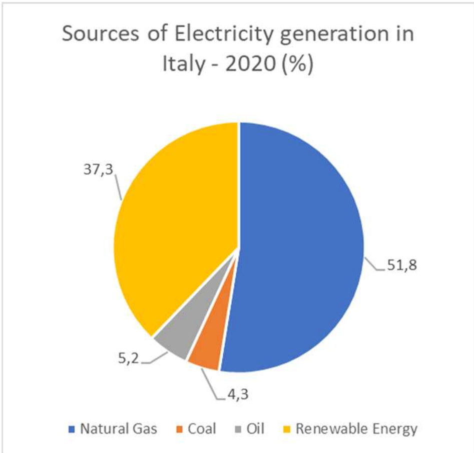

Figure 4.4-6: sources of electricity generation in Italy - 2020

Considering the following EU-MIX for power generation, the complete Well-to-Tank emissions were estimated by averaging the data collected above.

Considering the obtained values and knowing that the plant will be running 24 hours a day, the complete emissions for the year were also computed, making an excess approximation and not considering the 14-days stop for maintenance operations. We supposed that 1 MW of electric energy is needed for each 6 MW LHV of DME produced. Results are reported in Table 8.

Table 8: results of WTT analysis for DME production

TOTAL WTT CO2 EMISSIONS	48.5	g/MJ
CO2 EMISSION/DAY	62.2	g/s
CO2	1960.7	t/year
CO2 EMISSIONS - PRODUCTION	12.1	g/MJ_DME

After estimating the Well-to-Tank emissions of electricity fed to the DME production plant, the remaining Tank-to-Wheel emissions were computed. For this study, the emissions estimated assume the chosen IVECO

EUROCARGO E6 truck, considering the same engine specifications and its outputs. Results are reported in Figure 4.4-7

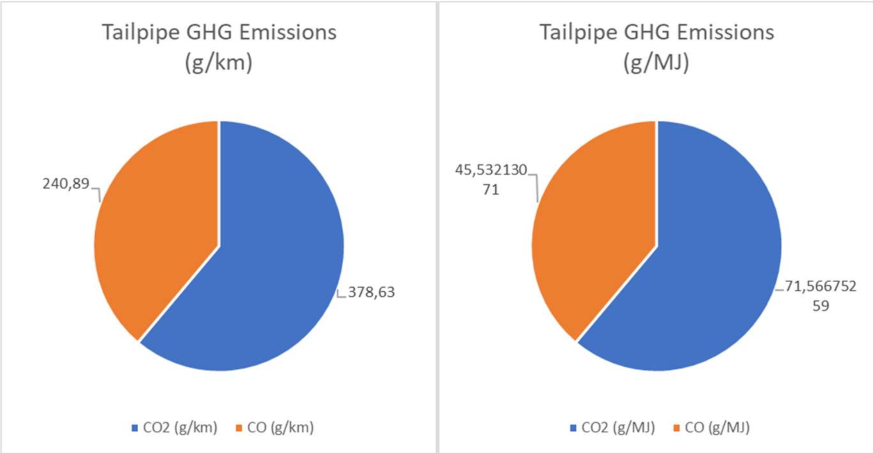

Figure 4.4-7: TTW emissions of DME

4.4.3. Comparison between Diesel and DME

After final computations of emissions estimates, the objective remains to compare both the fuels. The detailed comparison is depicted in Figure 4.4-8.

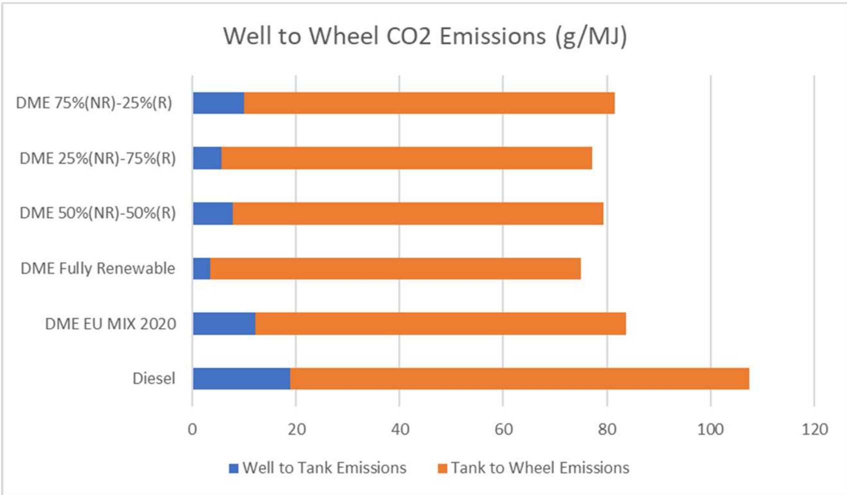

Figure 4.4-8: WtW emissions - comparison between Diesel and DME

These results show a reduction in overall CO_2 emissions (g/MJ) with DME compared to Diesel under EURO 6 Standards.

5. ECONOMIC EVALUATION

5.1. Economic Analysis

In this part we will describe our techno-economic analysis for the process of establishing a closed economy to produce DME from MSW to fuel our garbage collection truck fleet.

5.1.1. Sizing and costs of components

From the sizing of the production plant in terms of feed and yield shown in Table 9, and according to the yield of biomass from the MSW collection process, we started sizing the plant components considering a direct DME synthesis as shown in Figure 5.1-1.

Table 9: feed and yield for/from the plant

MATERIAL	IN	OUT	UNIT
BIOMASS	10.68	-	MW
CO2 PRODUCED	-	0.18	Kg co2 /sec
DME PRODUCTION	-	4.03	mol/sec
DME PRODUCTION	-	668.83	Kg/h
DME PRODUCTION	-	0.19	kg/sec
WATER	8799.42	-	ton/year
ELECTRICITY	1.282	-	MW

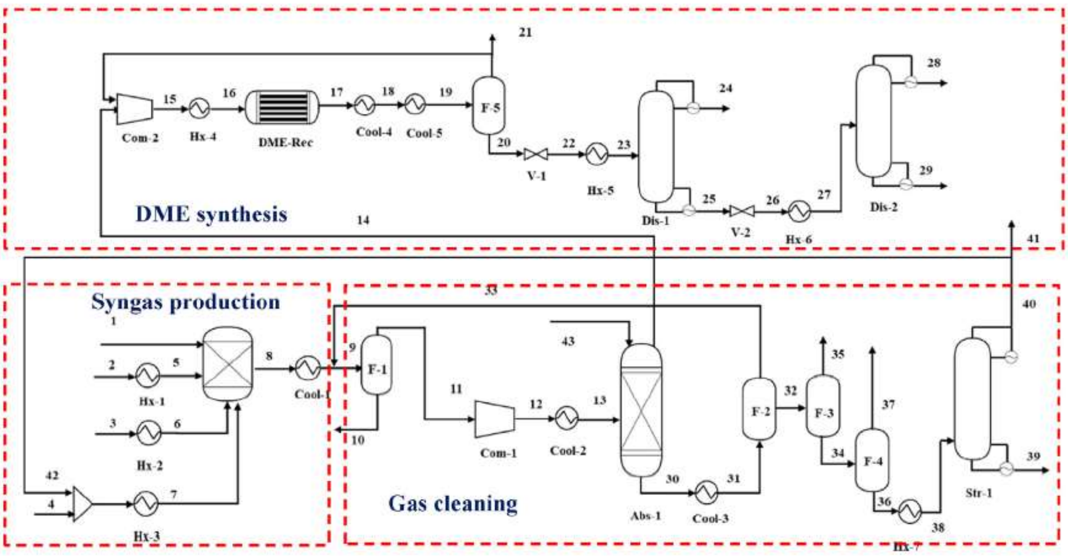

Figure 5.1-1: scheme of the plant and the components

As shown above, the main components of the production plant are:

1- Heater

2-Gasifier

3-Cooler

4-Absorber and stripper

5-Compressor

6-DME reactor

7-Distillator

Form the capital investment costs and economic assumptions shown in **Errore. L'origine riferimento non è stata trovata.**, the sizing of each component in our plant with done using the equation:

$$Cost_2 = Cost_1 * (\frac{Size_2}{Size_1})^{Scaling\ Factor}$$

Table 10: economic assumptions per component

COMPONENT	BASE CAPACITY	UNITS	SIZE (MILLION $)	SCALING FACTOR	REF YEAR
HEATER	138.1	Mwe	8.1	0.6	2002
GASIFIER	400	MW LHV biomass	28.99	0.7	1999
COOLER	110	MWe	11.12	0.6	2002
ABSORBER AND STRIPPER	90.83	kg/s co2 removal	43.38	0.7	2002
COMPRESSOR	10	MWe	6.3	0.67	2007
DME REACTOR	2.91	kmol/sec	18.03	0.65	2007
DISTILLATION	6.75	kg/sec	28.4	0.65	2007
ELECTRICITY	0.25	MW EE/ MW LHV_DME	0.2	$/KWh	-

Sizing the components yielded the numbers shown in Table 11 for the capital investments per component.

Table 11: CAPEX of each component

COMPONENT	CAPACITY FOR EACH COMPONENT IN OUR PLANT	UNITS	CAPITAL COST (M$)
HEATER	3.68	Mwe	0.92
GASIFIER	10.68	MW LHV biomass	2.29
COOLER	2.93	MWe	1.26
ABSORBER AND STRIPPER	0.17	kg/s co2 removal	0.55
COMPRESSOR	0.26	MWe	0.56
DME REACTOR	0.004	Kmole/sec	0.25
DISTILLATION	0.19	kg/sec	2.75
TOTAL CAPEX OF THE PRODUCTION PLANT	-	--	8.59

The results shown above yield a specific CAPEX of **0.8038743** $/watt which is considered reasonable according to the literature.

As shown in Figure 5.1-2, the distillatory and gasifier account for almost 60% of the capital costs.

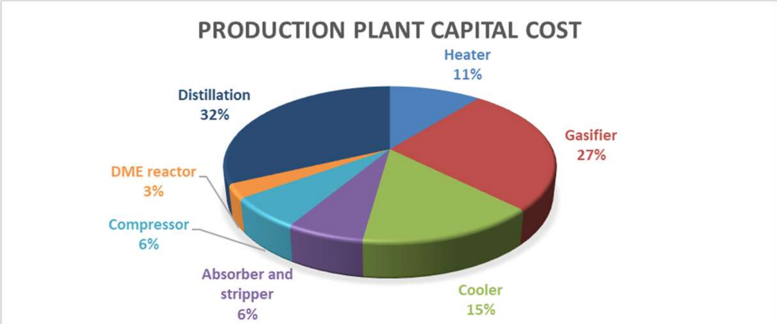

Figure 5.1-2: share of CAPEX per component

For the operating and Maintenance costs it was assumed that it's equal to **15%** of the capex in one year while the cost of electricity was taken to be equal to 0.21 $/kwh which is the price of electricity for businesses in Italy. Our plant is consuming annually 11.23 GWH to produce the required amount of DME.

Table 12: annual operating and management costs

OPERATING COSTS	AMOUNT	OPERATING COST (M$/YEAR)
OPERATION AND MAINTENANCE	15% of capex/year	1.28
ELECTRICITY	0.21 $/kwh	2.33
TOTAL OPEX	-	3.62

5.1.2. Costs related to external materials

In this part of the analysis, the costs of both water feed used to form steam for the gasification and the cost of bio-mass separation from organic MSW collected are considered, as shown in Table 13.

Table 13: feed costs

FEED	UNITARY COST	UNIT	COST OF FEED (M$/YEAR)
BIOMASS (MSW AND BIO-MASS SEPARATION)	126.66	$/ton	3.18
WATER	4.59	$/ton	0.04
TOTAL FEED COST	-	-	2.90

The Biomass separated from solid waste will reduce the amount of waste that has to be dumped into landfills eventually, which in return will reduce the plant cost by being paid to rent landfills. These savings are taken into consideration by assuming that each ton of waste costs 53.72 $ of landfill rent costs, and the annual landfill costs savings is equal to the mass of biomass fed to the plant x 53.72, as shown in Table 14.

Table 14: landfill costs savings

SAVINGS	UNITARY COST	SAVINGS (M$/YEAR)
LAND FILL COST	53.72 $/ton	1.35

5.1.3. Taxes, collection process and wages

In this section we take into consideration the economics of the collection process in terms of collection fees paid by citizens, the cost of the collection process and wages paid to employees as shown in Table 15.

Table 15: collection process economics and assumptions

COLLECTION PROCESS CASH FLOWS	UNITARY COST	UNIT	CASH FLOWS PER YEAR (M$/YEAR)
COLLECTION FEES PAID BY CITIZENS	5	$/citizen/month	130.816
COLLECTION AND TRANSPORTATION COSTS	600	$/ton	-118.126848
WAGES	800	$/employee/month	-4.128948369
NUMBER OF EMPLOYEES	4	employees/truck	-
TOTAL REVENUES	-	-	8.560203631

Now with all the data mentioned above which includes all the cash inflows and outflows involved in the DME production process, the levelized cost of DME can be calculated using this formula:

$$LCOF - DME\ from\ MSW = \frac{CAPEX + OPEX + Total\ Feed\ cost - Revenues - Savings}{Quantity\ of\ DME\ Produced}$$

Table 16: levelized cost of DME produced from MSW

LCOF DME Production from MSW Collected	0.875704475	$/kg DME
	0.586721998	$/l DME
	31.72842301	$/GJ DME
	28.55558071	Euro/GJ DME

If we compare the calculated LCOF for DME with Diesel, which has a LCOF around 20 euro/GJ, we can see that DME-LCOF is around 42.7 % higher than Diesels.

To reduce this value and try to bring it closer to diesel, we have considered the CIC bonds since the inter-ministerial decree of 2 March 2018 promotes the use of biomethane and other advanced biofuels in the transport sector.

This represents a strategic provision that aims to encourage the use of renewable sources in transport, also through the development of circular economy initiatives and of virtuous management of urban waste and agricultural waste. We can have an additional cash-in flows as shown in Table 17.

Table 17: CIC bond revenues

CO2 BONDS (CIC) (ref: GSE)		
CIC VALUE	375.00	€
BIOFUEL EMISSION	5	Gcal
J TO CAL CONVERSION	0.238846	cal
DME PRODUCED	21’344.19	MJ/h
DME PRODUCED	186*1e6	MJ/year
DME PRODUCED	44’658	Gcal/year
N OF CIC DUE	8’932	CIC/year
ECONOMIC VALUE	3.35	M€/year

By considering the Economic value of the CIC bonds as revenues in our calculations for LCOF-DME, we can reach a value of 12 euro/GJ which is almost half the value of LCOF-Diesel. Dropping the collection fees paid by citizens and considering the CIC bonds revenues in the LCOF will keep the LCOF around 28 Euro/GJ.

Some additional costs were not considered in the calculations of the LCOF for DME production for their irrelevance in the fuel production process itself.

Nevertheless, the trucks that will be operated with DME will need adjustments to their fuel injection system and their tanks to maintain the same range for the vehicle. Those modifications have been assumed to cost 7000 euro/truck. The refueling stations will also need some adaptations to their storage tanks and pumps which has been estimated to cost 250’000 euro/ station.

The additional costs shown in Table 18 will increase the CAPEX of the project to reach 10.34 M€.

Table 18: adaptation costs

ADDITIONAL CAPITAL COSTS	NUMBER OF UNITS	UNIT	CAPITAL COST (M$)
ADAPTATION COST OF TRUCK	1	Trucks	0.756
SERVICE STATIONS ADAPTATION	4	Service Stations	1

5.1.4. Selling opportunities

Our plant is sized with a capacity of 10.7 MW LHV of biomass intake which is categorized as a small scale DME production plant.

With this capacity, the plant yields 16 tons of DME per day and is able to completely fuel 108 trucks daily. In our collection process simulation, the number of trucks was increased to 157 due to the complexity of geographically covering the whole municipality of Milan with only 108 trucks.

As seen in Par. 4.3, the trucks are not emptying their tanks completely every day due to the short distances covered compared to their full range, the total trucks’ fleet consumption per day is only 2.9 tons of the daily production which is around 18 %.

This introduces the potential of excess capacity utilization in a way that would generate revenues. The revenues generated can be used to reduce the collection fees paid by the citizens. Therefore, it is important to perform this analysis to understand whether it’s more efficient to reduce investment costs and downsize the plant or to keep the current designed capacity and make use of the excess capacity to get an economical benefit.

Table 19: revenues coming from the sale of DME on the market

CURRENT EXCESS DME AMOUNT OFFERED TO THE MARKET	4831.5	Ton/year
DME SELLING PRICE	900	$/ton
TOTAL REVENUES	4.35	M$/year

With the revenues generated, the collection fees further drop from 4.9 $ (Considering CIC bonds revenues) paid on average by each citizen monthly to 4.7$. The collection fees can be furtherly dropped controlling the selling price of the fuel (Figure 5.1-3). Nevertheless, due to the usage of DME in the collection trucks locally produced through a circular economy, the collection process expenses are expected to drop also which is something we didn’t account for in our calculations.

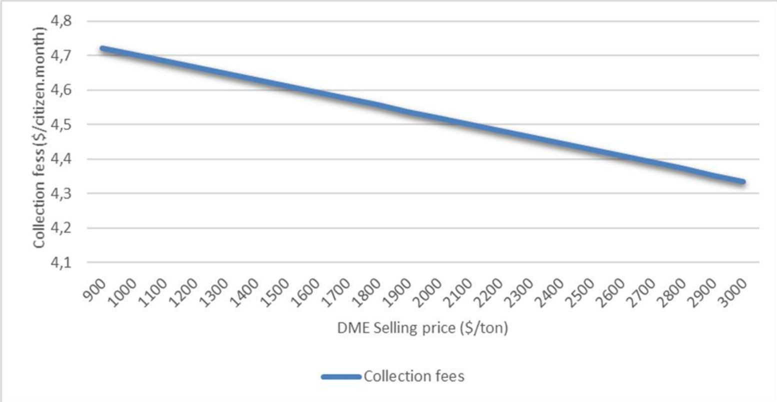

Figure 5.1-3: drop of collection fees per citizen

In conclusion for the economic analysis, this project has the potential to environmentally, economically, and financially benefit all stakeholders involved and the gains that can be generated from such an idea are not few and beneficial on more than one challenging front.

5.2. Sensitivity analysis: technical-economic improvements

For our sensitivity Analysis we consider the following performance and economic indices for the plant:

- Fuel Efficiency (from biomass to DME):

$$\eta_{fuel} = \frac{\dot{m}_{DME}.LHV_{DME}}{\dot{m}_{biomass}.LHV_{biomass}}$$

- Estimates of investment costs for innovative units
- Biomass, consumables, and O&M
- Electricity bought

For the design analysed previously the gasification efficiency stands at 0.6 and SEDMES efficiency stands at 0.8, we report in Table 20 the main performance and economic indexes:

Table 20: performance indexes for the original scenario

$\boldsymbol{\eta_{fuel}}$	48	%
CAPEX	8.6	M$
OPEX	3.6	M$/year
FEED COST	3.2	M$/year
ELECTRICITY COST	2.3	M$/year
LCOF	28.5	Euro/GJ

Next, we will compare our design to two assessed FLEDGED process concepts which are the F1-baseline case and the F3-Hydrogen case (Figure 2.3-1).

<u>F1-baseline case,</u> where the novel SEG and SEDMES process units are integrated in a biomass to DME plant also including biomass pretreatment, syngas cleaning, syngas compression and DME purification units, based on conventional technologies.

<u>F3-Hydrogen case,</u> which includes an electrolysis system, can provide hydrogen when the renewable electricity price is sufficiently low. This case involves reducing the amount of CO2 separated in SEG and an increase of the carbon ending up in the final fuel, enhancing the overall DME yield.

In the final project report of FLEDGED (Guandalini & Romano, 2020), the techno-economic performance has been evaluated. The baseline Fledged plant F1 has an overall fuel efficiency of 58.5% mainly deriving from the gasification efficiency of 74.1% and the SEDMES fuel Efficiency of 75.2%. When operated in the enhanced mode (Case F3), hydrogen addition increases overall fuel efficiency up to 93.3% (referred to biomass input only, 65.7% considering the hydrogen energy input). The consumed electricity is converted into DME with power to fuel efficiency of 53%.

Applying the same values of gasification and SEDMES efficiency for the F1 on our design the following values for performance indices are achieved (Table 21):

Table 21: performance Indexes applying the F1-basecase FLEDGED Scenario

η_{fuel}	55.7	%
CAPEX	8.95	M$
OPEX	4.1	M$/year
Feed cost	3.2	M$/year
Electricity cost	2.71	M$/year
LCOF	31.6	Euro/GJ

Comparing the two scenarios we can see that fuel efficiency has increased from 48% to 55.7% and it's very comparable to the value reported in the FLEDGED report. The LCOF of the fuel has increased by 10.9 % due to the increase in the CAPEX, OPEX and feed cost following the increase in the yield and the retrofits to increase the efficiency of the gasifier from 60% to 74.1%.

For applying the F3-Hydrogen case on our design we assumed a fuel efficiency of 93.3 % referred to the biomass input which is the value reported in the final report (Guandalini & Romano, 2020). Achieving this value will increase the DME yield to 0.36 kg/sec compared to the previous flow rate of 0.185 kg/sec. This will be obtained by injecting hydrogen at a rate of 0.01 kg/sec. Then the electrolyzer and its electric consumption are computed, and the results are the following (Table 22):

Table 22: electrolyzer specifications for applying the F3 FLEDGED Scenario

ELECTROLYZER SPECIFICATIONS		
CAPEX	0.44	M$/MW
CAPACITY	47	Kwh elec/ kg H2
SIZE	1.7	MW
ELECTRICITY PRICE	0.21	$/kwh

This new retrofitting of the electrolyzer and the H2 injection yields the following performance indices (Table 23)

Table 23: performance indexes after simulating the F3-Hydrogen case FLEDGED scenario

η_{fuel}	93.3	%
CAPEX	11.3	M$
OPEX	9.3	M$/year
FEED COST	3.2	M$/year
TOTAL ELECTRICITY COST	7.6	M$/year
LCOF	38.76	Euro/GJ

Comparing the three scenarios:

Table 24: performance indexes for the three Scenarios

PERFORMANCE INDEX	OUR SCENARIO	F1-BASE CASE	F3-HYDROGEN CASE	UNIT
η_{fuel}	48	55.7	93.3	%
CAPEX	8.6	8.95	11.3	M$
OPEX	3.6	4.1	9.3	M$/year
FEED COST	3.2	3.2	3.2	M$/year
TOTAL ELECTRICITY COST	2.3	2.71	7.6	M$/year
DME YIELD	0.18578744	0.214816727	0.361124336	Kg/sec
LCOF	28.5	31.6	38.76	$/GJ

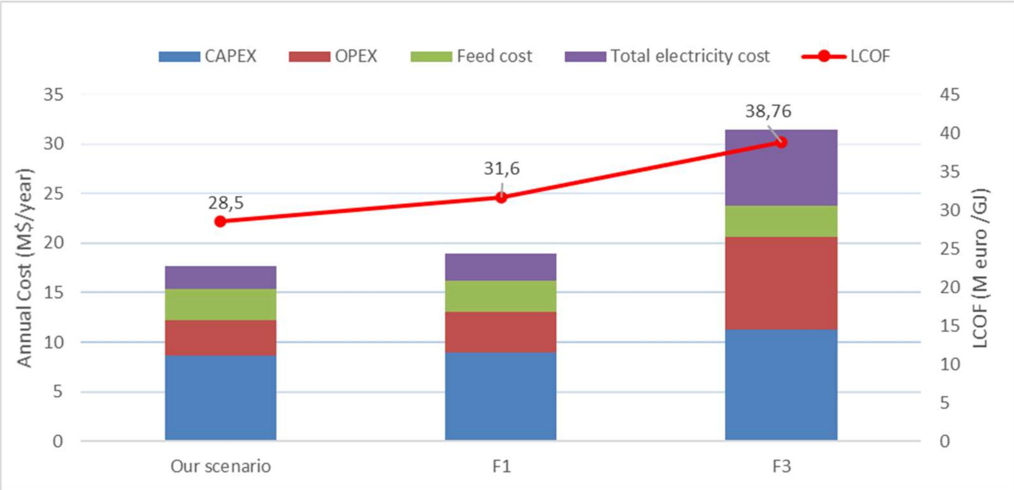

Figure 5.2-1: comparison of the three scenarios

Looking at the performance indexes for the three scenarios, we can see that our scenario provides the lowest LCOF, yet the lowest DME yield also, while scenario F1 provides a reasonable LCOF and a slightly higher DME (10.9 % higher DME yield).

However, scenario F3 provides almost double the DME yield but at a 36% higher LCOF. This is mainly because scenario F3 significantly increases the CAPEX and Electricity consumption cost due to the electrolyzer retrofitting. This would not be a very good choice for our plant and, as mentioned by the FLEDGED project report, both the F1 and F3 were simulated for 100 MW LHV biomass inlet plants while our plant is a 10.7 MW one.

Both options F1 and F3 are not recommended for small scale production plants like ours. Nevertheless, there is the small-scale FLEDGED plant using waste derived fuel from Econward process (case E1) (Econward, 2020). This plant features a global fuel efficiency of about 59 % which, when simulated on our design, didn't yield much different results from the F1 scenario in terms of DME yield but it increased the LCOF more than in the F1 scenario.

In conclusion, we recommend the original scenario for a competitive LCOF and the F1 scenario for a slight bump in the DME yield which might be needed in the future, but at the expense of an increase in the LCOF, which is due to the costs associated with the distillation and the DME reactor when the mass flow rate of the DME is increased.

6. CONCLUSION AND DISCUSSION

In this project, we performed an analysis on the possibility of implementing a plant for synthetising DME in the region of Milan, in Northern Italy.

The scope of the project was the one of analysing a possible circular economy in which MSW produced by the municipality becomes a resource for a cleaner fuel, instead of being a source of waste that needs to be disposed of in landfills.

We performed a technical analysis on the feasibility of our plant, computing not just the amount of DME produced per day but also the amount of trucks that can be refilled with this DME and the cost of switching them from diesel propulsion to DME propulsion.

We calculated the logistic optimization of the collection process, coming to the conclusion that the two alternatives proposed for the size of the tank do not affect the daily processes of collection, but instead allow us to sell part of the DME yielded. We also computed the WtW emission analysis for DME production, as well as the diesel one, making a comparison between the two.

We analysed the economic feasibility of the plant and of the overall process, considering also the possible incentives that can be obtained as of today by inserting on the market advanced biofuels like DME.

In the end, we referred to FLEDGED project to analyse the possible improvements that this state-of-the-art technology can bring to the plant. In order to fully exploit the potential of this technology, we would need to couple the municipality of Milan with other cities to arrive to the 100 MW LHV biomass inlet plant suggested by the studies. An option could be the one of coupling the municipalities of the largest cities of Lombardy like Milan, Bergamo, Brescia and Mantua.

Another possible option to make the production greener and furtherly reduce the GHG emission could be the one of using only energy coming from renewable sources, keeping in mind that we considered 1.5 MW of electric energy for each 6 MW (LHV) of DME produced. This would increase the overall cost, but with the right amount of incentives coming from the new climate regulations it could still be feasible.

As of today, the implementation of innovative and greener technologies needs to be supported with incentives and favored by regulations in order to make the LCOF competitive with respect to traditional fossil fuels. Further studies and improvements of this technology, like the ones proposed in the FLEDGED project, can yield a higher amount of fuel that can increase the amount sold on the market and not only used to keep the circular economy running.

Overall, the final conclusion of this project is the one that DME production for heavy duty sector, and its implementation in a circular economy framework, can be obtained if the conditions stated above are taken into account.

7. Index of tables

8. Index of images

9. Bibliography

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