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Chemical Carbon and Hydrogen Recycle through Waste Gasification: The Methanol Route

Alessia Borgogna, Gaetano Iaquaniello, Annarita Salladini, Emanuela Agostini and Mirko Boccacci

Abstract

A large amount of valuable Carbon and Hydrogen is lost in the disposal of the non-recyclable fraction of Municipal Solid Waste (MSW) – particularly unsorted waste fraction and plastics residue from mechanical recycle process. The waste-to-chemical technology allows to exploit the components entrapped in the non-recyclable waste by converting it into new chemicals. The core of waste-to-chemical technology is the gasification process, which is designed to convert waste into a valuable syngas to be used as example for methanol production. Waste to methanol schemes allow to achieve significant environmental and economic benefits, which can be further intensified within the scenario of increasing share of renewable energy.

Keywords: Waste gasification, carbon recycle, methanol, hydrogen

1. Introduction

By now, it is undeniable the (negative) impact that human activities have on environmental and climate conditions. The concentration of CO₂ in the atmosphere has reached 415 ppm [1]; a value which has no comparison throughout mankind history, and even before [2].

The discrepancy between the rate at which humans consume fossil resources and the earth's capability of absorbing emitted carbon and reproducing natural carbon resources is glaring [3]; and it represents the rationale behind the climate change issue. Therefore, this is today the problem to tackle.

To such end, three conceptual typologies of intervention can be identified. Reducing the emissions deriving from human activities; resorting to different (renewable) carbon sources; directly helping the planet absorb CO₂ in excess. These three interventions do not exclude one another – i.e., they can be deployed simultaneously. As a matter of fact, every kind of contributions may result essential to avoiding reaching the point of no return in relation to earth's climate change.

As for the first type of intervention, emissions can be abated by directly reducing our consumption. This can be achieved by limiting the use of throwaway material; by applying sharing and sustainable mobility [4]; by increasing environmental efficiency of each productive process – i.e., limiting the emissions of CO₂ per unity of product achieved.

Second type of intervention – which has a lower impact on our habits and lifestyle. Using a source of carbon which could be timely reproduced – algae represent one of the most recent examples thereof [5]. However, attention must be paid to the compatibility of the source exploitation with other environmental and social constraints, water usage and food production competition. Indeed, European Commission adds to the criteria for environmental evaluation of biofuels the Indirect Land Usage Change (ILUC) factors [6].

Third and final type of intervention. Technology and innovation should also serve the ambitious aim of finding systems able to remove the CO₂ excess already present in the atmosphere. An example thereof is direct capture of CO₂ from air, which, however, is far from being economically competitive. As a matter of fact, by 2019 only 15 plant with an overall capacity of about 9 ktCO₂ captured per year have been implemented [7]. This value is quite far from 30 Gton/y of CO₂ which is the reduction of emissions estimated to be required for limiting the global warming below 2°C [8].

Conversion of waste into a chemical encompasses both the first and the second type of intervention. In this way, waste is utilized as a source of carbon and hydrogen, thus representing a renewable source which is produced at a sufficiently high rate directly through the community, thus being (quite) proportional distributed and available, without any geographical restriction. About 2 billion Mtons per year of waste are globally produced. By 2050 it is foreseen to reach 3.4 billion of Mtons, due to the expected increase of population and GDP, which both influence waste production value per year [9]. Further, this source does not imply indirect usage of land, on the contrary it is a clever alternative to landfill.

As a matter of fact, both chemical production and waste disposal imply high greenhouse gases (GHG) emissions. Integration of these two processes into one allows to significantly reduce overall emissions.

What described above is only one of the successful aspects of the waste-to-chemical process. Economical aspect is also a favorable factor of a kind of process able to simultaneously convert waste and produce chemicals. Differently from what has been commonly seen till now, regarding chemical production economics, the main sources of income are two: - the usual one, the selling of the product; – the unconventional one, a gate fee for the feedstock, i.e. a payment for the disposal of the waste.

The waste fractions which are taken into account as sources in the waste-to-chemical process are indeed fractions which alternatively would have been disposed through – at worst – landfilling or – at best – incineration with energy recovery. While, the waste-to-chemical process allows carbon and hydrogen recovery, i.e. contextually material and energy recovery.

Refuse Derived Fuel (RDF), dry fraction of unsorted fraction of Municipal Solid Waste (MSW), and unrecycled fraction of plastic sorted waste, are kind of waste eligible for the waste-to-chemical process. It is worth noting that these fractions come from social and technological constraints relating to the practical recyclability of MSW.

The waste-to-chemical process allows to convert the mentioned kinds of waste thank to its core section, a high temperature melting gasifier. Here, due to the high temperature reached, the combustible part of the feed is converted into valuable syngas, meanwhile the inorganic part is melted and then vitrified. A completely inert residue is produced. Further, it can be also used for rockwool production or as inert filling in the civil sector material. Thus, zero residue from MSW can be reached, by integrating the waste-to-chemical process with technologies for material recycle available by now.

The syngas produced can be applied for methanol production, after tailored syngas purification. The chapter includes a technical, economic and environmental

assessment of the overall technology, from waste conversion to methanol production. Two possible schemes are exposed, the second one integrates a base waste to methanol process with electrolysis, showing how waste to chemical is a feasible technology able to accompany process industry in the pathway of energy transition.

2. High temperature gasification for waste valorization

As already mentioned, waste feedstock like Municipal solid Waste, Refuse Derived Fuel (RDF) and plastics residues, due to the high content of carbon and hydrogen, may be considered a sort of alternative and sustainable feedstock. Typical compositions for the above-mentioned waste are reported in the **Table 1**. As shown by the elementary composition, carbon content varies in the range 30–60%w while hydrogen in the range 4–7%w.

If properly converted, these kinds of wastes may be used in substitution of conventional fossil feedstock building a new chemistry pathway allowing to produce conventional chemicals in a more sustainable way [10].

Under this scenario technology plays a major role in the fully implementation of circular economy around the concept of waste as feedstock for industrial processes. This paradigm implies a robust and reliable technology able to manage the heterogeneous nature of waste as well as their pollutants content.

The proposed technology allowing to convert waste into chemicals, is based on a high temperature gasification process carried out under pure oxygen environment. A schematic view of gasifier reactor allowing to perform such conversion is shown in **Figure 1**.

The gasifier reactor consists of three sections: the melting zone (1600°C), where exothermic reactions and melting of inert compounds take place; the gasification zone (600–800 C°), where low oxygen-content brings to partial oxidation reactions; the stabilization zone, where a further introduction of auxiliary fuel and oxygen lead to an increase of temperature (1100°C) ensuring tar degradation, full decomposition of the long chain organic molecules and inhibition of dioxins formation.

Multiple injection of oxygen and auxiliary fuel along the reactor, take temperature in order of 1600–2000°C in the bottom, 600–800°C in the middle up to 1100–1200°C on the top. Such temperature profile assures a full conversion of waste into

Component	Value	RDF	PW
Wet basis			
C	% weight	33–38	47–61
H	% weight	4–5	5–7
O	% weight	16–18	14–20
N	% weight	0.2–1.0	0.2–0.5
S	% weight	0.02–0.15	0.02–0.3
Cl	% weight	0.8–1.5	0.8–1.5
Moisture	% weight	17–21	5–9
Inert	% weight	17–25	7–20
LHV _{wet}	MJ/kg	14–16	21–24

Table 1.
Typical elementary composition of PW and RDF and relevant LHV values.

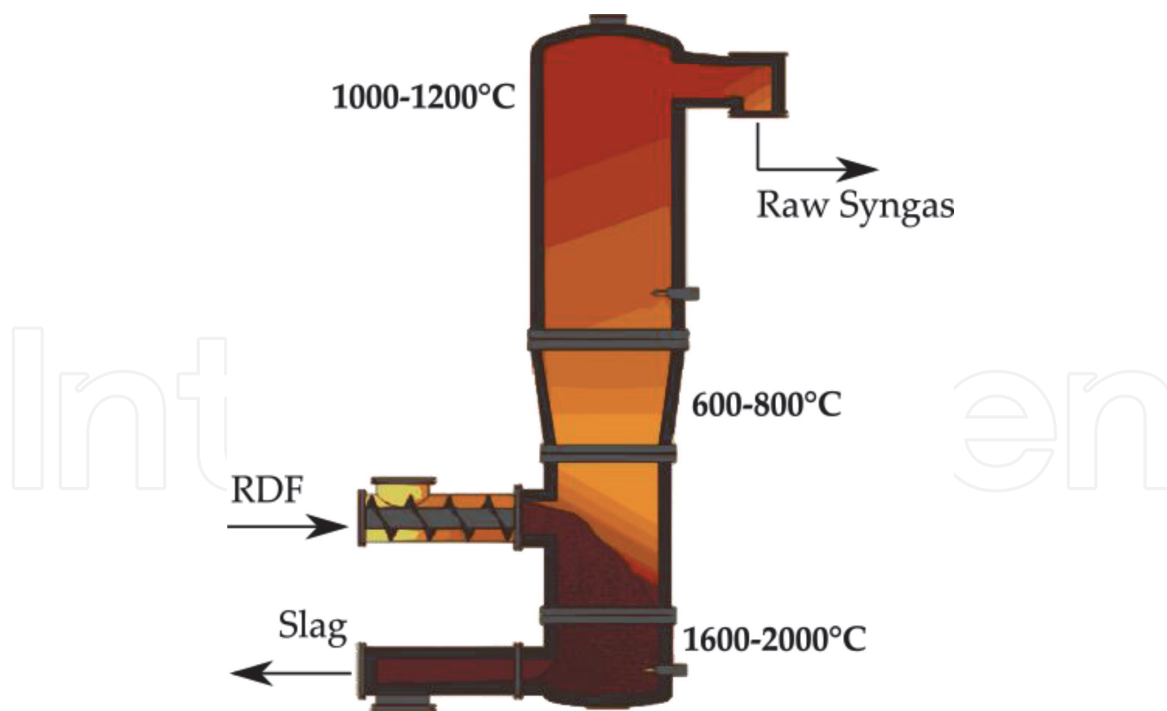


Figure 1.
High temperature gasification reactor.

two products: a high valuable syngas rich in H_2 , CO and free of char, tar, dioxin and furans (Iaquaniello et al. 2018) discharged from the top of reactor and an inert vitrified material discharged on the bottom [11]. The high temperature held on the melting zone allows to discharge the inert components of waste (mineral and metals), in a granulated and vitrified state ideally carbon free. Depending on local legislation, such material can be valorized into cement or construction industry otherwise disposed as standard waste.

As reported by Salladini et al. [12], the syngas yield and relevant composition, are mainly affected by the LHV value and C/O ratio. On the overall higher LHV results into higher syngas yield as well as higher content in terms of CO and H_2 and lower concentration of CO_2 . Produced syngas contains as major components CO , H_2 , CO_2 and under minor content volatile metals and any particles up drafted with the syngas. **Figure 2** reports a block diagram of the gasification section, preliminary cleaning and syngas purification section.

As first step the hot gas is routed to an evaporative quench where temperature is abruptly reduced down to $85\text{--}90^\circ\text{C}$ by direct injection of water. Although there is a loss of high temperature heat, this rapid cooling freezes chemical composition achieved at high temperature avoiding any undesired reaction. The two-phase mixture at the bottom exit of quench is routed to a sedimentation tank. This unit allows to collect on the bottom the sludge, continuously removed from the system, and clarified water reused as cooling water in the quench. The Sedimentation works under low pH condition (1.5–3) in order to promote the migration of volatile metals in liquid phase. The syngas exiting the sedimentation tank is routed to an acidic column that further promote the metal removal.

Syngas exiting from the acidic columns of each gasification line is collected and sent to a common section based on alkaline scrubbing column, wet electrostatic precipitators (WESP) and subcooling column. Water stream collected from the bottom of the washing columns due to the potential content of pollutants are routed to the WasteWater Treatment unit.

Gasifier works under quite atmospheric pressure achieving at the end of cleaning section pressure in order of few mbar above the atmospheric pressure. It

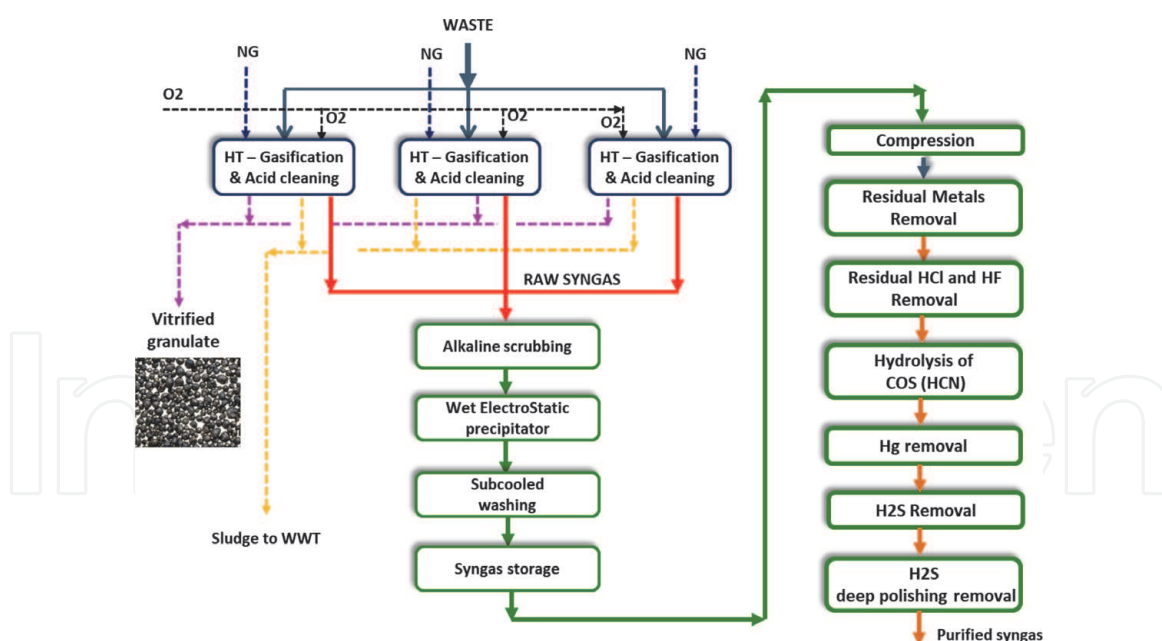


Figure 2.
Block scheme: Gasification and syngas primary gas cleaning.

derives that a compression section is needed before routing the syngas to downstream section. In order to assure stable condition in terms of syngas pressure and flowrate at suction of compressors, a gas holder is installed between the gasification section and compression.

The cleaned syngas still contains sulfur compounds mainly in the form of H_2S and COS together with residual chlorine, HCN and trace of Hg. Once compressed, syngas is routed to the purification section involving the following step: removal of residual dust and metals, removal of HCl, hydrolysis of the COS and HCN, H_2S removal through an oxy-reduction system and a final polishing step based on zinc oxide absorbents in order to reduce sulfur content down to ppb as required by catalyst adopted for downstream synthesis.

The high temperature regime and the use of a waste as feedstock, requires dedicated maintenance work around the gasifier aiming at preventing damages on refractory materials and avoiding excessive fouling along the quench wall and sedimentation. On this regard a plant architecture based on multiple gasification lines working in parallel is foreseen in order to assure plant availability during maintenance operation: when a gasification line is kept shut down for maintenance service, the other lines are kept under maximum capacity to assure a continuous syngas production with a minimum reduction of productivity.

The purification procedure described above, delivers a syngas suitable to be fed to catalyst-based synthesis. Depending on selected end product, a conditioning step aiming at adjustment of H_2 and CO content is required [13, 14].

3. Waste to methanol scheme

The proposed waste to methanol case study will be developed around a waste feedstock having an average composition describing a mixture of 75% RDF and 25% plastic residues. Resulting mixture composition is reported in **Table 2**.

By applying the process scheme depicted in **Figure 2**, resulting syngas composition at the end of syngas cleaning (inlet compression) and downstream the purification step is reported in **Table 3**. A very low level of contaminants are achieved

Component	U.m.	Value
Wet basis		
C	% weight	38.9
H	% weight	5.3
O	% weight	21.5
N	% weight	0.85
S	% weight	0.20
Cl	% weight	0.94
Moisture	% weight	15.7
Inert	% weight	16.5
LHV	MJ/kg	16.0

Table 2.
Waste used for the case study (mixture 75% RDF-25% plastics).

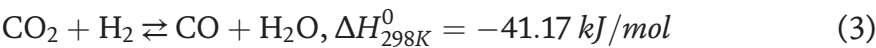
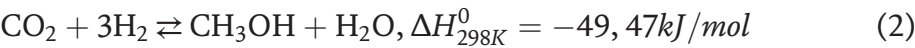
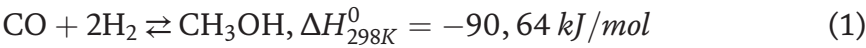
Downstream cleaning section		Downstream purification section	
Component	u.m.	Value	Value
H ₂	%mol	37.6	39.1
CO	%mol	41.0	42.6
CO ₂	%mol	12.4	12.8
H ₂ O	%mol	4.0	0.4
N ₂	%mol	4.6	4.8
CH ₄	%mol	0.21	0.21
Arg	%mol	0.03	
H ₂ S	ppm	930	0.01
COS	ppm	45	0.1
HCN	ppm	10	0.1
HCl	ppm	4.1	0.1
Hg	ppm	0.02	—
PM	ppm	0.3	—

Table 3.
Syngas composition.

through the proposed architecture thus accounting for a syngas to be used as building block for downstream synthesis.

To proper design the condition section, it is necessary to understand constraint required on syngas composition.

Methanol synthesis is based on the following catalytic reactions where only two are linearly independent:



According to the stoichiometry of reactions involved (1)–(3), a proper content of H_2 , CO and CO_2 has to be assured in the gas mixture fed to methanol loop. Such content is controlled by introducing the following parameter named Methanol Module (MM) is defined: $MM = (H_2 - CO_2)/(CO + CO_2)$.

The stoichiometric MM is equal to 2, thus a value of MM around 2.0–2.4, is generally recommended in the industrial plant [15].

As reported in **Table 3**, resulting syngas is characterized by a low value of MM (0.47) meaning that an excess of carbon or rather a deficit of hydrogen exists. In order to achieve required composition for methanol synthesis, two different approaches may be adopted. One option is to increase the hydrogen content through water gas shift reaction and reduce the resulting excess carbon in the form of pure CO_2 while another option is to add an external source of H_2 to balance the deficit. Such H_2 would be preferably produced from water electrolysis powered from renewable source in order to avoid any indirect fossil CO_2 emissions.

3.1 Waste to methanol scheme with internal hydrogen production

The process architecture for methanol production from waste based on internal hydrogen production, is depicted in **Figure 3**. As introduced above, without foresee any additional external source of Hydrogen, to comply the methanol module it is necessary to increase the internal H_2 content through water gas shift reaction by reacting CO and H_2O to produce CO_2 and H_2 .



To promote shift reaction, medium steam is mixed at the inlet of the shift reactor, operating with a steam/dry-syngas ratio at least of 1.5 in order to manage the shift exit temperature below $480^\circ C$. As shown by the stoichiometry, the shift reaction accounts for an increase of hydrogen content but does not allow any variation in the MM therefore a CO_2 removal system is required to achieve proper composition as per methanol module. To achieve a MM in order of 2.1, only a fraction of purified syngas has to be routed to the conditioning section based on shift reaction and CO_2 removal system [16]. The higher the fraction of syngas

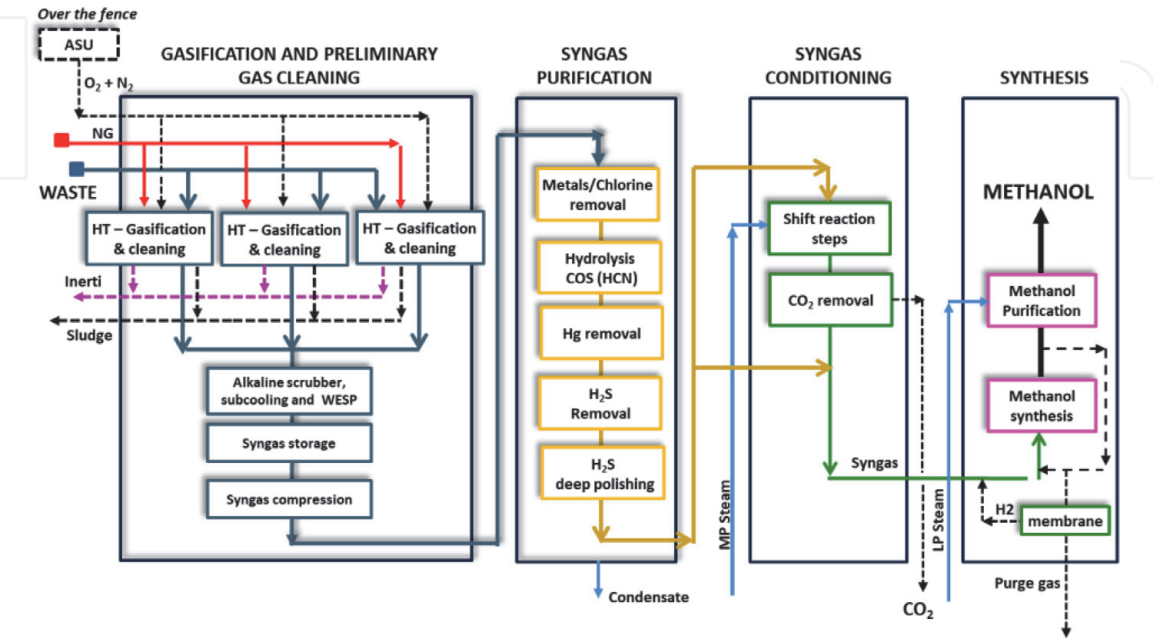


Figure 3.
Waste to methanol scheme with internal H_2 production (scenario a).

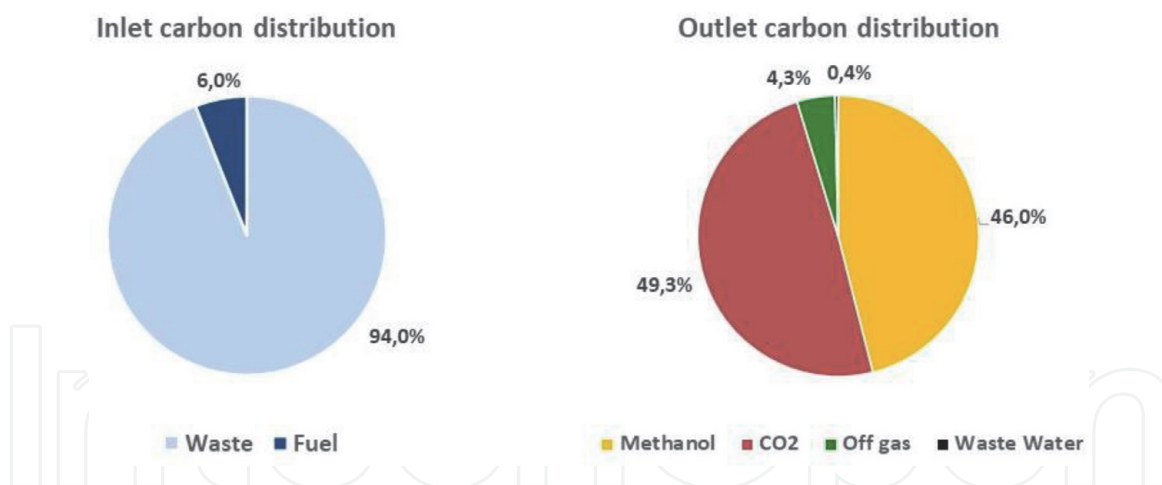


Figure 4.
Carbon distribution of the waste to methanol scheme with internal H_2 production. Scenario A.

conditioned, the higher is the carbon converted into CO_2 that means a lower fraction converted into final product. The sweet syngas coming from CO_2 removal system is reconnected with fresh syngas. To increase carbon utilization, a recovery of pure hydrogen through a membrane separation is applied on the bleed stream coming from methanol loop normally routed to combustion. The target value of $MM = 2.1$ at the inlet of methanol section, is thus achieved through the addition of H_2 recovered from methanol loop.

The resulting conditioned syngas is compressed and routed to the methanol synthesis reactor. The raw methanol is recovered by condensation and then purified via distillation in order to fulfill the required grade.

In the proposed architecture three gasification lines are adopted with an overall capacity of about 192.000 ton/y of waste and around 98.000 ton/y of methanol. As described above, the excess carbon contained in the waste is discharged as pure CO_2 to battery limits. It derives that it can be reused for any application ranging from food industry or other industrial application. Without any external H_2 addition, the proposed scheme based on feedstock reported in **Table 2**, allows to fix around 46% of incoming carbon into the methanol and to deliver at battery limits around 49% of carbon as pure CO_2 as shown by carbon distribution graph in **Figure 4**. The residual is discharged into the atmosphere as diluted flue gas. Such distribution accounts for a production of 1.07 ton pure CO_2 /ton MeOH and around 0,094 ton diluted CO_2 /ton MeOH as flue gas. A conventional methanol production scheme based on fossil feedstock performs higher direct CO_2 emission in the form of flue gas ranging from 0.52–0.70 ton CO_2 /ton MeOH once based on natural gas steam reforming, up to 1.4 ton CO_2 /ton MeOH once the reference scheme is partial oxidation of fossil oil [17].

Heat and material balance around the proposed scheme have been performed through Aspen Plus Process simulator. Main results in terms of products and by-product production as well as utilities consumption are reported in **Table 4**.

As shown in Block diagram depicted in **Figure 3**, a purge gas stream suitable to be used as fuel is delivered to battery limits. To take care of its residual calorific value, it was calculated the equivalent natural gas saving and properly considered in the OPEX evaluation.

3.2 Waste to methanol scheme with addition of external hydrogen

As discussed above, a different approach in managing the syngas composition characterized by an excess of carbon may be adopted. The latter consist into an

Feed/Product/bioprocess	Quantity per year	U.m.
Waste feedstock	192.000	ton/y
Methanol production	98.000	ton/y
Granulated	31872	t/y
Sludge	7520	t/y
Utilities	Quantity per year	U.m.
Electric Power	110720	MWh/y
Well water	256800	m ³ /y
Demi water	5600	m ³ /y
BFW	149037	m ³ /y
Medium Pressure (MP) steam	81936	ton/y
Low Pressure (LP) steam	126304	ton/y
Natural Gas	6456	ton/y
Instrument Air	10104000	Nm ³ /y
Nitrogen	12800000	Nm ³ /y
Oxygen	75840000	Nm ³ /y
Cooling water	23656000	m ³ /y
NG saving through off-gas energy recovery	2800	ton/y

Table 4.
Heat and material balance scenario a.

external addition of hydrogen in order to achieve a better carbon utilization. An overall simplification of process scheme is obtained considering that shift reaction and carbon removal system are no more required.

On this regards the conditioning section results into a mixing between the external Hydrogen stream and the purified syngas. Source of external hydrogen would be preferably derived from water electrolysis in order to benefit of the oxygen coproduced by the electrolysis.

Corresponding process scheme is reported in **Figure 5**.

In this scenario for the same overall waste capacity of about 192.000 ton/y, the Methanol productivity is quite doubled reaching a value of around 196.000 ton/y. Such architecture allows to fix around 92.5% of carbon in the final end-product thus reducing to around 7% the amount lost in the off gas (**Figure 6**). The resulting direct emission factor is equal to 0.075 ton diluted CO₂/ton MeOH with a consistent reduction in comparison to conventional routes. In terms of direct CO₂ emissions, the Scenario B allows for a better valorization of carbon contained in the waste increasing the fraction transferred into the product.

Of course, looking at indirect CO₂ emission, the overall environmental performance of this configuration will be directly related to emission of the electric energy source in terms of ton CO₂/MWh.

Main results of Heat and material balance around the H₂ assisted Waste to Methanol scheme is reported in the **Table 5**.

Due to the high electric energy consumption associated to the use of electrolysis, this figure becomes feasible from economic and environmental point of view under low electric energy price and high sharing of renewables into the electric energy system.

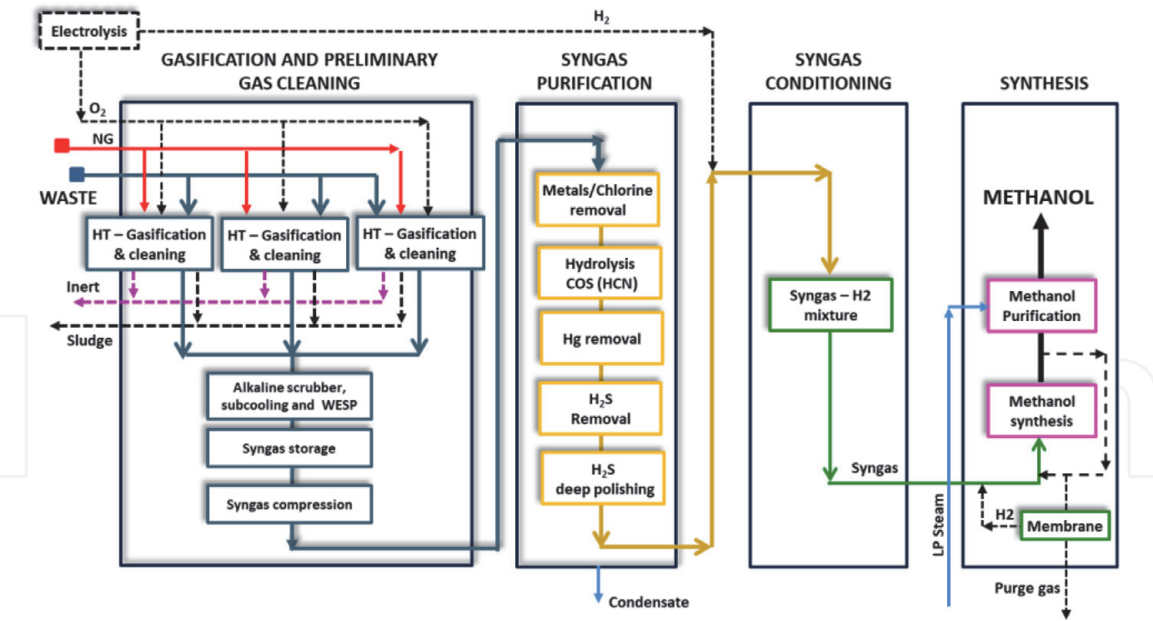


Figure 5.
Waste to methanol scheme with external H₂ addition (scenario B).

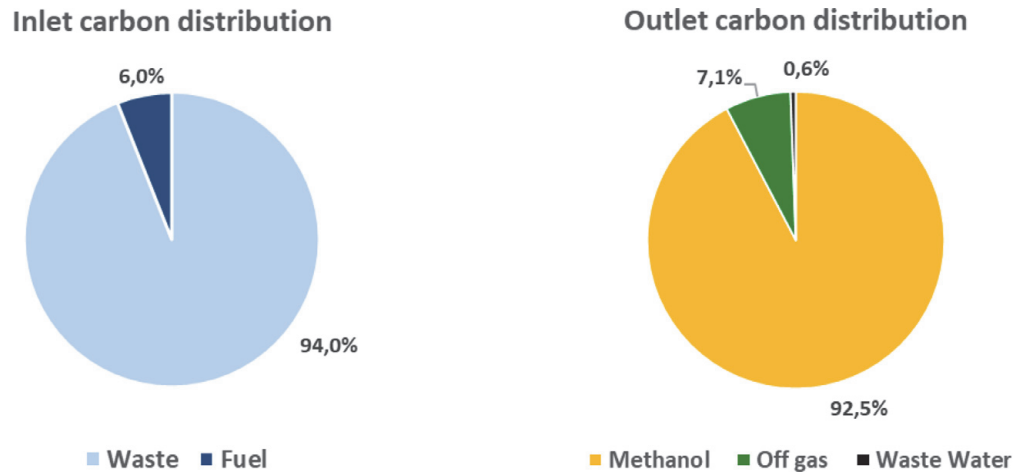


Figure 6.
Carbon distribution of the waste to methanol scheme with external H₂ addition.

4. Evaluation of methanol cost of production

In order to assess the economic feasibility of the waste to methanol technology, an economical evaluation has been carried out based on Capital EXpenditures (CAPEX) and OPERating EXpenditures (OPEX) around the above-described schemes: the scenario A where syngas conditioning is performed by internal hydrogen production at the expense of CO, and scenario B where syngas conditioning is achieved through external H₂ addition.

The overall CAPEX has been evaluated starting from the cost of equipment and applying proper multiplying factor to take into account all cost contribution to the CAPEX (erection, civil work, engineering activities etc.) (Table 6) [18].

In order to evaluate OPEX and related methanol cost of production, the following assumptions in terms of specific cost of utilities has been adopted (Table 7).

On the basis of utilities consumption derived from heat and material balance (Tables 4 and 5), OPEX for the two scenarios have been estimated as reported in Table 8.

Feed/Product/bioprodukt	Quantity per year	U.m.
Waste feedstock	192.000	Ton/y
Methanol production	196.000	ton/y
Granulated	31872	t/y
Sludge	7520	t/y
Sulfur cake	680	t/y
Waste water	88000	t/y
Utilities	Quantity per year	U.m.
Electric Power process consumption	165798	MWh/y
Electric Power electrolysis	936000	MWh/y
Well water	503328	m ³ /y
Demi water	176189	m ³ /y
BFW	292113	m ³ /y
MP steam	0	ton/y
LP steam	126304	ton/y
Natural Gas	6456	ton/y
Instrument Air	10104000	Nm ³ /y
Nitrogen	12840000	Nm ³ /y
Oxygen	0	Nm ³ /y
Cooling water	45404820	m3/y
NG saving through off-gas energy recovery	1021	ton/y

Table 5.
Heat and material balance scenario B.

	Scenario A	Scenario B
	M€	M€
CAPEX ISBL	193	214
ELECTROLYSYS	—	128
CAPEX OSBL	35	40
Contingency (10%)	22	38
TOTAL	250	420

Table 6.
CAPEX estimation for methanol case study.

Taking into account a capital structure based on 30% equity and residual 70% as bank loan, the corresponding methanol Cost of Production (COP) results into 243 €/ton and 522 €/ton for the scenario A and B respectively.

By considering a market price of grey methanol currently estimated in order of 390€/ton for the European Market [19] a minimum conservative price of 400 €/ton has been considered as market price for the *circular* methanol. On such basis the Internal rate of Return (IRR) has been estimated as a function of main parameters.

For the Scenario A, IRR has been evaluated as a function of methanol market price and waste gate fee (**Figure 7**). The base case performs a project IRR around 11% thus assessing a reasonable profitability.

Cost component	Value
Waste treatment ton/year (three gasification lines)	192000
Vitrified granulate produced ton/year	32000
Concentrated sludge produced ton/year	7500
Maintenance cost as % of the CAPEX	2%
Depreciation	0.0872
Equity (20 year and 6% interest rate)	0.0672
Bank loan (12 year and 3% interest rate)	
Personnel (at company cost) M€ per year	1.75
7 people per shift (7x5) = 35 people	0.24
3 specialist all over the working day	0.12
1 Manager	
RDF-Plastics price € per ton	150
Electric energy cost € per MWh	70
Natural gas price, € per Sm3	0.24
MP steam cost, € per ton	28.3
LP steam cost, € per ton	24.2
O2 cost, € per Nm3	0.078
N2 cost, € per Nm3	0.078
Instrument air, € per Nm3	0.028
Raw water, € per m3	0.08
Cooling water, € per m3	0.014
Demi water, € per m3	0.43
Cost slag disposal € per ton	40
Cost concentrated sludge disposal € per ton	200
Electrolytic H ₂ consumption, KWh per Nm ³	4.5
Electrolytic cost € per kWh	1100

Table 7.
Assumption list for economic evaluation.

To proper assess the impact of methanol price and gate fee, sensitivities analysis has been carried out varying the Methanol market price in the range 400–500 €/ton and the waste gate fee in the range 130–160 €/ton.

For the scenario B, due to the high impact on power consumption, project IRR has been estimated as function of electric energy price.

As shown in **Figure 8**, electric energy cost in order of 30 €/MWh allows to achieve project IRR comparable with those obtained with the Scenario A.

5. Estimation of CO₂ emission for the waste to methanol technology

For a better understanding of potential carbon footprint reduction of the proposed Waste to Methanol technology, a simplified LCA analysis has been performed.

The use of waste as feedstock for chemical synthesis allows to fulfill at the same time two different services: from one side the disposal of waste and from the other the synthesis of a chemical in this case methanol. It derives that such system compared with conventional route of waste disposal represented by incinerator and

Utility	M€	M€
Electric Power	7.86	11.77
Electric power electrolysis	—	66.46
Well water	0.02	0.04
Demi water	0.002	0.076
BFW	0.22	0.44
MP steam	2.32	—
LP steam	3.06	3.06
Natural Gas	2.13	2.13
Instrument Air	0.28	0.20
Nitrogen	1.00	1.93
Oxygen	5.95	—
Cooling water	0.33	0.33
Granulated	1.27	1.27
Sludge	1.50	1.50
Chemicals	0.50	0.50
Others	1.00	1.00
NG saving through off-gas energy recovery	−0.93	−0.34
Variable cost subtotal	28.21	90.37
Maintenance	4.60	7.65
Labor cost	2.01	2.28
TOTAL OPEX	34.78	100.30
Depreciation (Equity)	6.54	12.20
Bank loan repayment	11.76	18.82
TOTAL COST + DEPRECIATION + BANK LOAN	53.08	131.06
REVENUES		
From WASTE gate fee	28.80	28.80
COP (€/ton)	243	522

Table 8.
OPEX and COP estimation.

chemical synthesis from fossil feedstock, allows for a better exploitation of carbon and at the end for a saving in terms of CO₂ emissions. The below evaluation is referred to the entire life of products that means taking into account also emission related to the use of methanol. The proper estimate the CO₂ saving of the waste to chemical approach, the following formulation has been adopted:

$$CO_2 \text{ saving} = \frac{(CO_{2Conv.methanol}) - (CO_{2Waste \text{ to Methanol}} - CO_{2Incinerator})}{CO_{2Conv. \text{ methanol}}} \quad (5)$$

5.1 Emission of conventional methanol production

The estimation of CO₂ emission for conventional methanol production, takes into consideration that equivalent emission for feed and fuel is around 75% of the

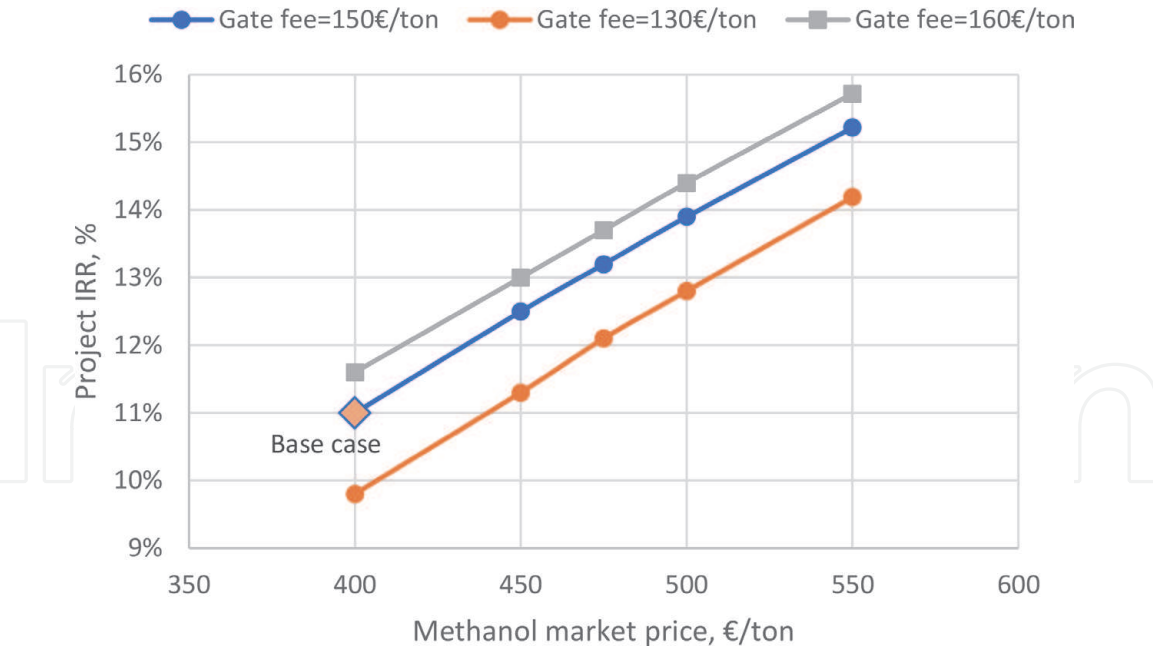


Figure 7.
Project IRR evaluation vs. methanol price and gate fee.

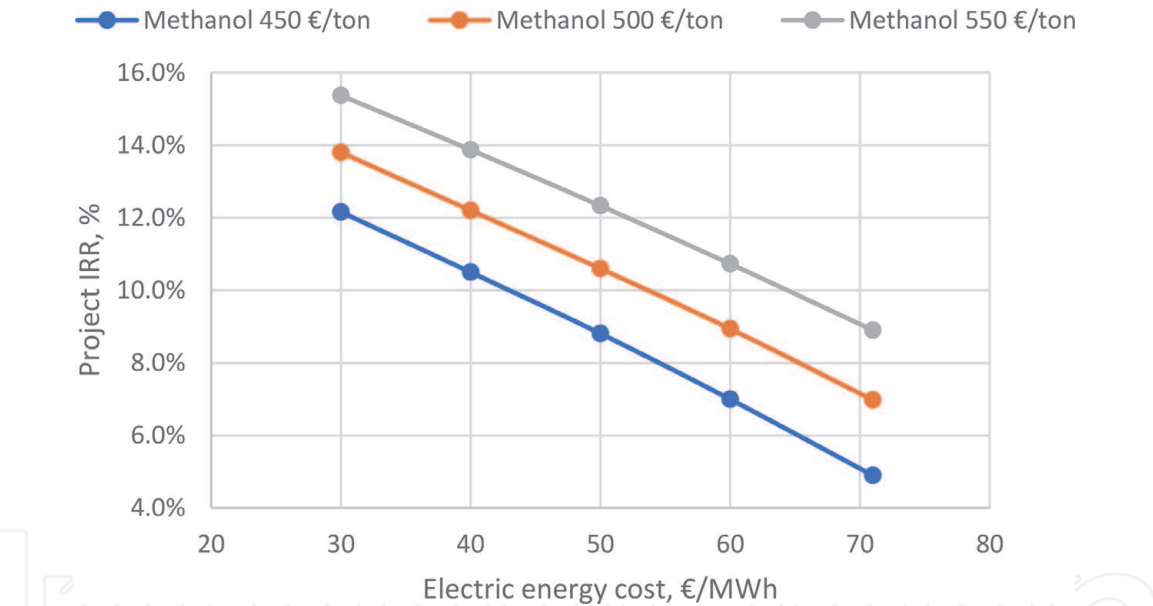


Figure 8.
Project IRR evaluation vs. electric energy price and methanol market price. SCENARIO B.

overall LCA emission. An average feed & fuel consumption for conventional methanol plant equal to 32,7Gcal/ton methanol has been assumed [20]. The resulting specific emission to be taken into account for the above-mentioned criteria is around 2.5 tonCO₂/ton MeOH.

5.2 Emission of incinerator

For the incinerator it is adopted the reference value of around 2tonCO₂/tonWaste. To proper account for the equivalent CO₂ emission deriving from electric power no more produced from waste and needed to be replaced from the grid, it is assumed an electric energy efficiency of 28%. It derives that 24 t/h of waste having a calorific value of 16MJ/kg, considering also a combustion assisted with natural gas in

order of 2% of energetic content of waste can produced 30.5 MWe. This electric power no more produced from waste needs to be replaced by electric energy from the grid.

5.3 Emission of waste to methanol

For the waste to methanol plant the following contribution have been taken into account:

C1 = CO₂ emission derived from all carbon contained in the waste which along the process is converted into CO₂. Considering the reference waste composition, this contribution is in order of 2.8 tonCO₂/ton Methanol distributed into methanol, flue gas and concentrated CO₂.

C2 = CO₂ emission derived from fuel consumption. This contribution considers not only the direct fuel consumption but also the equivalent consumption for steam used along the process. The overall consumption is in order of 0.257 ton CO₂/ton Methanol).

C3 = CO₂ emission derived from fugitive emission of natural gas used along the project calculated as 2,5% of natural gas consumption [21] with a Methane GWP equal to 28 [22]; the resulting value is in order of 0.061 tonCO₂/ton Methanol.

C4 = Equivalent CO₂ emission to replace electric energy no more produced from waste incinerator. Resulting amount of equivalent CO₂ is in order of 0.61 tonCO₂/ton Methanol on the basis of a grid electric emission factor of 0.245 kgCO₂/kWhe.

C5 = Indirect CO₂ emission for electric energy absorbed along the process; resulting value is in order of 0.43 ton CO₂/ton methanol according to a grid emission factor of 0.245 kgCO₂/kWhe.

C6 = Equivalent CO₂ emission derived from transport of Waste from production facility assuming a distance between gasifier and waste facility of around 100 km. resulting specific consumption is 0.017 ton CO₂/ton methanol.

Taking into account the above contribution, the overall CO₂ emission for the waste to methanol plant is in order of 4.17 ton CO₂/ton methanol.

As shown in **Figure 9**, main contribution of CO₂ emission for the waste to methanol approach, without considering Carbon contained in the waste and released as flue gas, pure CO₂ and product, is addressed to electric energy. The latter accounts for electric energy consumed by the process and that replacing the electric

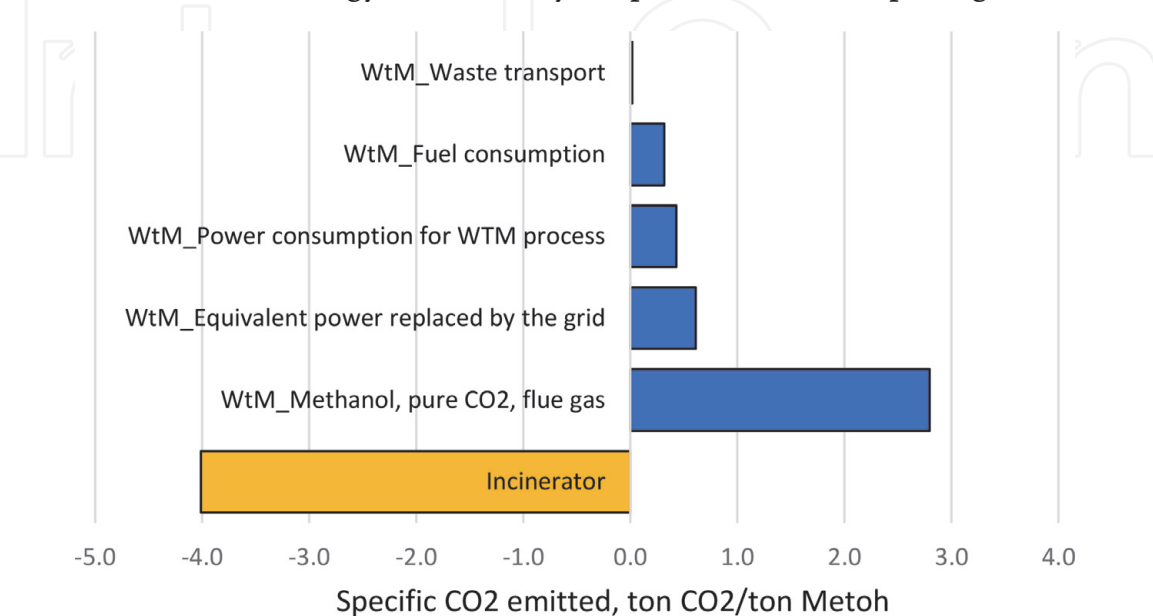


Figure 9.
Net LCA CO₂ emission of the waste to methanol scheme (SCENARIO B).

energy no more produced from waste. Under a scenario where it is expected an increasing share of renewables into the global energetic system, the CO₂ saving of the Waste to Chemicals approach has the potential to be further increased. The overall saving achieved by the waste to methanol plant, according to a simplified LCA analysis, is in order of 94% corresponding to around 229.000 tCO₂/year.

6. Conclusion

Waste like RDF, Municipal Solid Waste and residue plastics, once properly converted into syngas, may be used as feedstock for the synthesis of wide range of chemicals. This approach fulfills the hierarchy of waste management being addressed to waste no more recyclable and normally routed to incinerator or land-fill. The key step allowing for a reasonable use of waste as alternative feedstock, is the primary conversion step based on a high temperature gasification carried out under pure oxygen environment and with a temperature profile assuring certain characteristics for produced syngas.

The case study here analyzed based on methanol production from waste, resulted in a feasible solution from technical, economic and environmental point of view. Competitive cost of production may be achieved with the scenario A under Gate fee in order of 140–150€/ton. Scenario based on external hydrogen addition as per Scenario B, although accounting for a strongly reduction of direct CO₂ emission, needs of a cheap electric energy cost, in order of 30€/MWh, to be competitive.

The simplified LCA analysis performed around the waste to methanol scenario, shows the consistent benefit of proposed solution in terms of CO₂ emission. The waste to Methanol scheme fulfills two different service: from one side the disposal of a waste and from the other the synthesis of a chemical. Under this scenario, once compared with conventional methanol production based on fossil feedstock, a saving of CO₂ emission in order of 94% may be achieve. The latter, for the reference capacity accounts for an avoidance of around 229.000 tCO₂/y.

Taking into account the increasing sharing of renewable expected for the future, the CO₂ avoidance of the Waste methanol scheme may be further increased.

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