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Flexible pathways for green methanol production: A comparative technoeconomic analysis of Biomass and Solar Energy

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Abstract:

The transformation of energy systems towards low-carbon models requires sustainable solutions that can be easily integrated into existing infrastructure and multiple sectors. In this context, renewable methanol stands out as a flexible energy carrier with several applications in transport, energy generation, and the chemical industry, making it a potential sector for decarbonisation. Two primary pathways dominate the landscape: Bio-methanol derived from biomass waste through anaerobic digestion, steam reforming, or gasification; and E-methanol synthesised from captured CO_2 with green hydrogen generated from renewable electricity via photovoltaics. The cost of E-methanol is expected to decrease from 800-1600 USD/t to a competitive range of 250-630 USD/t by 2050, while mitigating emissions through carbon capture. In comparison, literature estimates bio-methanol cost at 565-630 €/t, potentially reaching conventional methanol cost by 2030, with a carbon footprint of 3 to 34.4 g CO2 eq/MJ. The viability of both routes depends on factors such as regional resource availability, energy costs and economies of scale. However, most existing studies analyse them separately or under non-comparable assumptions. This study addresses a techno-economic comparison of the potential of bio-methanol and e-methanol in the European context, tailoring the analysis to the industrial and geographical realities of the studied regions. The analysis shows that the relative competitiveness of the two routes vary significantly across regions and future cost scenarios. The results show that bio-methanol can be economically competitive in rural regions, while e-methanol is advantageous in developed industrial regions with high renewable surpluses. This analysis expands previous knowledge by identifying specific conditions under which each route is optimal. The obtained results suggest that a diversified strategy for renewable methanol production can reduce risks and accelerate decarbonisation in Europe, providing relevant information for energy policy design and investment decisions.

Keywords:
Methanol; Bio-methanol; E-methanol; Renewable Energy; Hydrogen.

1. Introduction

In the European Union, 78.6% of CO_2 emissions correspond to sectors that highly rely on the use of fuels, such as energy generation (27.4%), domestic transport (23.8%), industry (20.3%), and the maritime and aviation sectors, which collectively account for 7.1% [1]. These statistics show a great potential for green fuels deployment, capable of drastically reducing CO_2 emissions in hard-to-abate sectors and therefore becoming a promising solution for the industry and transport sector decarbonization. The development of sustainable fuels solutions are essential to meet the ambitious objective of quadrupling their use by 2035 compared to

2025 levels [2], serving as a critical intermediate milestone toward achieving final carbon neutrality by 2050 [3].

Among the diverse range of renewable energy carriers, methanol emerges as a premier candidate due to its inherent physical and logistical advantages over alternatives like ammonia or hydrogen. The primary advantage of methanol lies in its liquid state under ambient conditions. In contrast, ammonia requires liquefaction via compression to approximately 10 bar at room temperature or cooling to -33°C. Similarly, hydrogen suffers from extremely low volumetric density, necessitating cryogenic storage at -253°C or very high-pressure tanks for viable transport [4]. Methanol possesses a high hydrogen content, establishing it as one of the most promising H_2 carriers currently available [5,6]. Its compatibility with existing liquid-fuel infrastructure significantly reduces logistical costs and avoids the need for massive capital investments in new distribution networks [7]. In the same line, methanol can be utilized directly in various existing internal combustion engines, making it a favorable replacement for gasoline and diesel [8], particularly given its specific energy of 20 MJ/kg.

By replacing fossil-derived inputs with bio-based and synthetic routes, methanol can be transformed into a carbon-neutral energy carrier and a sustainable chemical building block. This direction aligns with the EU vision and objective of decarbonising the industry and transport sectors through regulations such as the Fuel EU Maritime regulation, targeting a reduction on 80% of GHG by 2050 with additional rewards to ships using RFNBO until 2033 [9], or the ReFuelEU Aviation, which requires a minimum share of 20% of SAF and 5% synthetic fuels in aviation by 2035 [10]. However, high production costs remain a significant bottleneck for green methanol, particularly in the case of e-methanol. While technological maturity is advancing and commercial plants such as European Energy Kassø [11] or CRI & Jiangsu Sailboat [12] are already operational, the robustness of the sector is still uncertain. An example of this drawback is the Swedish Orsted FlagshipONE project, which was intended to be Europe's largest e-methanol facility, but was forced to cease construction due to insufficient market readiness and high economic barriers [13].

Currently, two primary pathways exist for green methanol production: bio-methanol, derived from biomass, and e-methanol, produced via synthetic routes. Both offer the potential for carbon-neutral or even carbon-negative lifecycles. While bio-methanol cost is generally lower, its efficiency and total yield are limited by the specific type and quantity of local feedstock. In contrast, e-methanol processes lead to higher fuel cost, but offers rapid industrial decarbonization by utilizing captured CO_2 and local renewable capacity. In regions where grid injection might be limited for renewable sources, this positions fuel synthesis as an ideal solution for balancing the power sector, as it absorbs the renewable surpluses.

Despite the existence of global studies on biomass potential, the impact of specific feedstock compositions requires localized evaluation to be technically accurate. Similarly, e-methanol implementation demands region-specific analysis to address the availability of capturable emissions and the synergy with renewable energy sources available for high-energy water electrolysis. This study addresses this research gap by comparing two specific regions with different resource profiles, evaluating the production potential for both bio-methanol and e-methanol, and analyzing the corresponding resource constraints. Additionally, the process energy demand (electrical and thermal) is compared for the studied cases.

The following sections provide a structured analysis, beginning with a definition of the primary production routes and the presentation of the regions under study in Section 2. Section 3 details the methodology used to evaluate yield and energy consumption, while Section 4 presents the comparative results. Finally, a comprehensive economic assessment of both green methanol pathways is conducted in Section 5.

2. Green methanol potential in Europe

Traditional methanol production relies on the thermochemical conversion of coal and natural gas, yielding "brown" and "grey" methanol, respectively. These fossil-based pathways are carbon-intensive and remain major contributors to industrial emissions. To address these environmental challenges, the sector is increasingly adopting renewable solutions, such as bio-methanol and e-methanol. Bio-methanol is most commonly derived from the gasification of sustainable biomass and organic waste, while e-methanol is produced through the catalytic hydrogenation of captured CO_2 using green hydrogen.

2.1. Bio-methanol

Bio-methanol has the advantage of utilising a wide variety of biomass feedstocks and producing a range of potential fuels through different conversion processes. However, some barriers must be overcome in the process, such as the need for pre-drying due to high moisture content, which significantly reduces thermal efficiency. High transport and storage costs are derived from the low bulk density of, which usually ranges within 80 – 220 kg/m^3 depending on the feedstock type [14]. Although the wide variety of biomass can be an advantage, it also implies different compositions that require a proper, customised design of the technology to optimise the conversion process.

Bio-methanol can be produced from biomass thermochemical conversion processes, mainly gasification, pyrolysis, and direct liquefaction, or from biochemical conversion utilising microorganisms and their enzymes, such as anaerobic digestion and fermentation. Alternative fuels can be produced through chemical processes such as transesterification [15]. The most common commercial process for syngas production is biomass gasification, which is carried out at around 700-900ºC and atmospheric or medium pressure in the presence of an oxidising agent, generally oxygen, air or steam [16,17].

2.2. E-methanol

E-methanol is synthesised via the power-to-liquid route, primarily through the hydrogenation of CO_2 captured from industrial sources (CCU), as Direct Air Capture (DAC) is not optimal for large-scale methanol production [18,19]. The process utilises renewable energy to produce hydrogen and generates syngas when combined with captured CO_2. This is converted into methanol, ideally using Cu/ZnO/Al2O3 catalysts at pressures of 20 - 100 bar and temperatures up to 300ºC [20,21]. Specific copper-based catalysts can achieve high methanol selectivity, up to 99–100%.

Although methanol synthesis ideally undergoes CO_2 hydrogenation as the main reaction, CO hydrogenation and Reverse Water-Gas shift (RWGS) reactions occur in parallel as well.

2.3. Locations studied in this work

This study primarily examines two main aspects: methanol production potential and the resource requirements. The regions under study were selected based on their varying resource availability to facilitate a comparative analysis. The selection criteria focus on three main pillars: industrial CO_2 emissions, biomass availability within a local radius and renewable energy sources, specifically solar power. This information is presented in **Table 1**.

***Table 1**. Selected locations characteristics*

Selected location	Area	Inhabitants	Biomass Availability	CO_2 industrial emissions
Province of Córdoba, Spain.	13.768 km^2 [22]	772.153 [23]	3.012,9 kt/y [24]	1.011,3 kt/y [25]
Metropolitan region Frankfurt Rhine-Main, Germany.	14.753 km^2 [26]	5.800.000 [26]	3.076,17 kt/y [27]	6.651 kt/y [28]

In this case, both locations have a similar biomass availability, while the Frankfurt Rhine-Main (FRM) region is much richer in industry, accounting for six times the CO_2 emissions of Córdoba.

3. Method

3.1. Bio-methanol potential and simulation

Biomass gasification and bio-methanol synthesis processes have been simulated in Aspen Plus. The oxidant agent on gasification is steam, since the syngas produced through this method presents higher LHV and quality than those produced using air or oxygen [17,29], and it’s the most economical option for methanol gasification and the lowest emissions pathway [29]. While energy demand increases because the reaction is endothermic, this offers the possibility of coupling the system with renewable sources, although this integration is not the focus of this work. As studied by some authors [30], syngas from biomass is usually hydrogen-poor for biofuels synthesis, and therefore CO_2 content must be partially removed or converted to fuel with additional hydrogen from external sources. This last option requires competitive cost for green hydrogen, and therefore the first option was considered for this study instead. **Figure 1** shows the process flow diagram, and **Table 3** presents the operating conditions of the most representative streams in the case of wheat straw gasification (values vary with biomass feedstock).

Table 2. *Thermodynamic hypotheses for the evaluation of bio-methanol synthesis*

Variable	Value
Biomass rate	1000 kg/h
Gasification temperature	900 ºC
Steam feed	500 kg/h
Compressors isentropic efficiency	80%
Methanol reactor conditions	250 ºC, 80 bar
CO_2 separator efficiency	85 % (CO_2 split fraction)

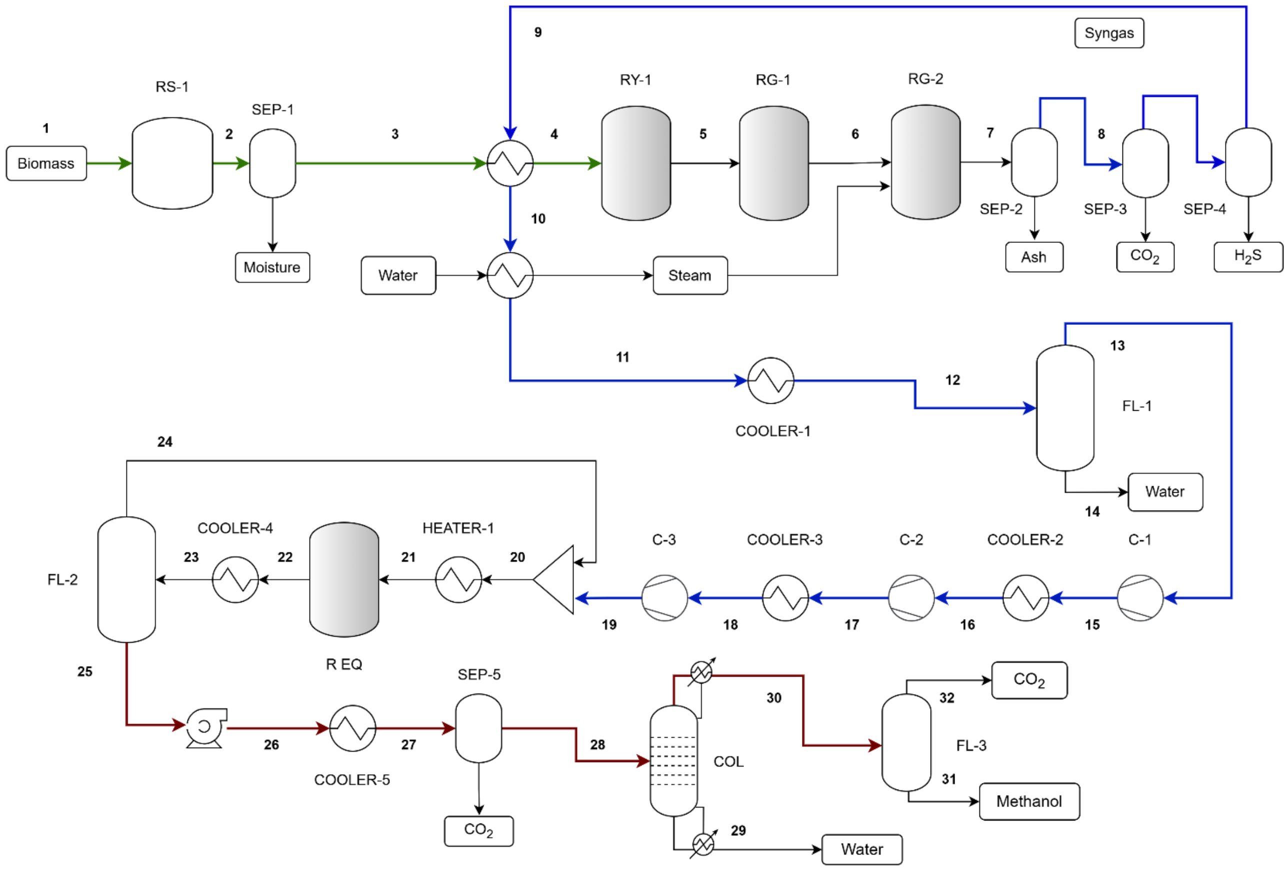

Figure 1*. Bio-methanol synthesis process flow diagram.*

RS-1: Stoic reactor to heat up the biomass and remove the moisture in it.

RY-1: Yield reactor to simulate the decomposition of the solid non-conventional biomass into elemental components. The elemental composition remains the same.

RG-1: Gibbs reactor to complete chemical equilibrium by minimizing Gibbs free energy.

RG-2: Gibbs reactor acting as the gasifier at 900ºC and 1 bar, with steam as oxidant agent.

R EQ: Equilibrium reactor acting as the methanol synthesis reactor.

Table 3. *Bio-methanol synthesis operating conditions in the case of wheat straw gasification*

Stream	Mass rate	Temperature	Pressure	Composition (% mol)
1	1000 kg/h	25 ºC	1 bar	Biomass
4	900.6 kg/h	250 ºC	1 bar	Dry biomass (non decomposed)
7	1400.6 kg/h	900 ºC	1 bar	Ash (3.5% mass) , H_2O (10.4%), H_2 (49.12%), N_2 (0.34%), CO (35%), CO_2 (5.77%)
12	1157.24 kg/h	40 ºC	1 bar	H_2O (10.9%), H_2 (51.68%), N_2 (0.36%), CO (36%), CO_2 (0.9%)
13	1083.8 kg/h	40 ºC	1 bar	H_2O (6.45%), H_2 (54.28%), N_2 (0.38%), CO (37.9%), CO_2 (0.96%)
19	1083.8 kg/h	329.6 ºC	80 bar	H_2O (6.45%), H_2 (54.28%), N_2 (0.38%), CO (37.9%), CO_2 (0.96%)
24	2749 kg/h	50 ºC	80 bar	H_2O (0%), H_2 (23.7%), N_2 (5%), CO (35.1%), CO_2 (34.4%), CH_3OH (1.37%)
20	3832.75 kg/h	250 ºC	80 bar	H_2O (2.88%), H_2 (37.34%), N_2 (3%), CO (36.3%), CO_2 (19.5%), CH_3OH (0.76%)
23	3832.75 kg/h	60 ºC	80 bar	H_2O (0.26%), H_2 (18.8%), N_2 (4%), CO (27.6%), CO_2 (30%), CH_3OH (18.7%)
25	938.1 kg/h	50 ºC	80 bar	H_2O (1.2%), H_2 (0.3%), N_2 (0.1%), CO (0.6%), CO_2 (13.6%), CH_3OH (84.17%)
31	742.8 kg/h	41 ºC	1 bar	CO_2 (0.3%), CH_3OH (99.7%)

The proximate and ultimate analysis compositions, retrieved from the literature or official reports, will vary with feedstock type and ultimately determine the operating conditions.

3.2. E-methanol potential and simulation

Industrial CO_2 capture is the primary limiting factor for e-methanol production. While CO_2 transport is technically feasible, this analysis assumes that a region's potential is determined solely by its local industrial emissions. Hydrogen production has not been simulated. Instead, a range of efficiencies and operating values, as represented in **Table 4**, has been drawn from the literature to assess the technology's wide variability.

Table 4. *Operational parameters covered for hydrogen production*

Evaluated parameters	Value range	Reference
Solar panels efficiency (1st and 2nd generation cells)	21,2% - 26,1%	[31]
PEM electrolyser: energy required to produce 1 kg of H2	40,52 – 75 kWh/kg H2	[32] [33] [34]
H2: CO2 ratio in the syngas feed to the reactor	3-5	[18]
Conversion of CO2 in the global plant	93,9 % - 100%	[18]
Methanol selectivity in the global plant	88% - 100%	[35] [18]

Methanol synthesis is simulated using a DWsim model, from H_2 and CO_2 compression through methanol distillation. The steam required for the distillation column is partially generated by cooling the reactor, requiring additional thermal energy ideally provided by renewable sources. Compressors' efficiency is 80%. The heat exchangers' temperature approach is 20 °C.

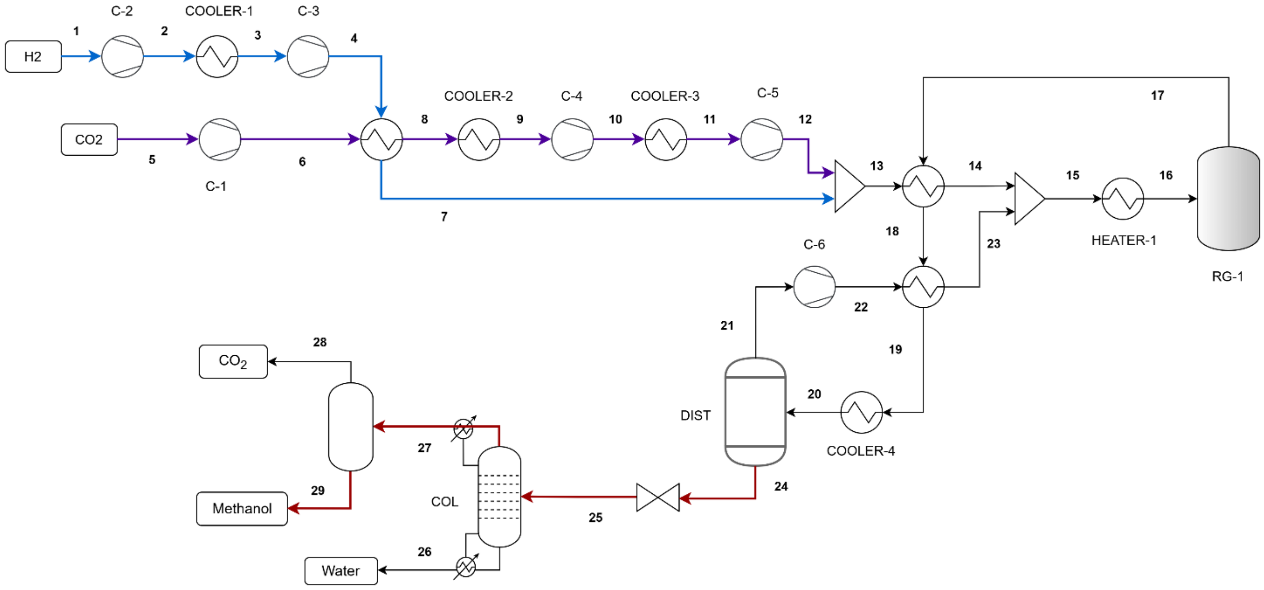

Figure 2. *E-methanol synthesis process flow diagram*

The operating conditions of the most representative streams are presented in **Table 5**.

Table 5. *E-methanol synthesis operating conditions*

Stream	Mass rate	Temperature	Pressure	Composition (% mol)
1	196 kg/h	25 ºC	30 bar	H_2 (100%)
2	1425.6 kg/h	25ºC	1 bar	CO_2 (100%)
12	1425.6 kg/h	100.7 ºC	80 bar	CO_2 (100%)
7	196 kg/h	182.4 ºC	80 bar	H_2 (100%)
14	1621.6 kg/h	230 ºC	80 bar	H_2 (75%), CO_2 (25%)
15	3618.34 kg/h	216.17 ºC	80 bar	H_2O (0.16%), H_2 (92.6%), CO_2 (65.4%), CH_3OH (0.7%)
16	3618.34 kg/h	250 ºC	80 bar	H_2O (0.16%), H_2 (92.6%), CO_2 (65.4%), CH_3OH (0.7%)
17	3618.34 kg/h	250 ºC	80 bar	H_2O (5%), H_2 (37.34%), CO_2 (2.3%), CH_3OH (5.6%)
20	3618.34 kg/h	60 ºC	80 bar	H_2O (5%), H_2 (37.34%), CO_2 (2.3%), CH_3OH (5.6%)
21	1998.07 kg/h	60 ºC	80 bar	H_2O (0.2%), H_2 (96.4%), CO_2 (2.5%), CH_3OH (0.85%)
24	1620.27 kg/h	60 ºC	80 bar	H_2O (49.6%), H_2 (0.2%), CO_2 (0.47%), CH_3OH (49.7%)
29	1000.69 kg/h	57 ºC	1.1 bar	H_2O (0.5%), CO_2 (0.13%), CH_3OH (99.37%)

The capacity factor of the methanol plant is 89% [36]. It is assumed that all energy is produced from renewable sources through the integration of electrical storage systems. The scenario in which all energy required by the process is supplied by photovoltaic systems is simulated. To estimate the photovoltaic installation area to satisfy these energy requirements, it is assumed that during solar hours, the energy captured must cover the energy needs at night. The range of solar radiation in the region is determined by the minimum and maximum values of the compilation of several locations spread across the corresponding region [37,38].

4. Results and discussion

4.1. Bio-methanol potential

Bio-methanol potential is directly determined by the regional availability and exploitation capacity of biomass. This study evaluates both the total annual yield (ton/year) and the specific feedstock share, details are provided in Table 6 and ***Table 7*** (with the studied feedstocks highlighted in bold). To ensure the analysis focuses on the most significant resources, the scope is limited to feedstocks with a potential share exceeding 2%, unless otherwise specified.

Table 6. *Biomass potential per feedstock in Córdoba, 2025 [24]*

Sector	Potential (kt/y)	Biomass Feedstock	Potential (kt/y)	Sector share %
Agriculture	764,22	Citrus	1,79	0,06%
		Fruits	0,45	0,01%
		Grape	14,14	0,47%
		Olive trees	**561,18**	**18,63%**
		Tomato	1,59	0,05%
		Cotton	**80,85**	**2,68%**
		Sunflower	**104,22**	**3,46%**
Industry	869,79	Meat Industry	4,62	0,15%
		Olive pits	**118,13**	**3,92%**
		Pomace oil	**655,27**	**21,75%**
		Olive mills leaves	**76,37**	**2,53%**
		Wood waste	1,75	0,06%
		Wine and liquor industry	10,86	0,36%
		Cotton Industry waste	2,74	0,09%
		Fishery Industry Waste	0,042	0,00%
Energy plantations [a]	344,97	**Corn**	**166,7**	**5,53%**
		Rapeseed	0,13	0,00%
		Sugarbeet	**112,7**	**3,74%**
		Sunflower	**65,4**	**2,17%**
Urban Residues	270,4	**FORSU (Organic Solid Urban Residues Fraction)** [c]	**65,4**	**2,17%**
		Used oil	4,78	0,16%
		Municipal Residual Water [c]	**137,1**	**4,55%**
		Digested Sludge from municipal water [c]	**54,41**	**1,81%**
		Gardens and parks waste	4,62	0,30%
Cattle raising [b]	565,92	-	-	18,78%
Forestry	197,63	**Forestry**	-	**6,56%**

[a] Energy plantation feedstock share is extrapolated from 2010 data [39].

[b] Waste from the cattle raising industry has not been included in this study

[c] Municipal Residual Water, Digested Sludge from municipal water and FORSU have been aggregated under 'Municipal water sludge' and share a common composition.

Table 7. Biomass potential per feedstock in Frankfurt Rhein Main, 2018 [40]

Sector	Potential (kt/y)	Biomass Feedstock	Potential (kt/y)	Total share %
Agriculture	1.510,78	**Cereal straw** [d]	**702,87**	**22,85%**
		Leaves [e]	**807,91**	**26,26%**
Industry	609,94	**Wood waste**	**344,451**	**11,20%**
		Paper and cardboard waste	**142,813**	**4,64%**
		Animal and mixed food waste	52,407	1,70%
		Vegetal waste	55,93	1,82%
		Common sludges	14,343	0,47%
Municipalities	842,12	Organic waste from households [f]	178,864	5,81%
		Gardens and parks waste	**151,682**	**4,93%**
		Paper and cardboard waste	**367,814**	**11,96%**
		Municipal sewage sludge	**143,756**	**4,67%**
Forestry	113,33	-	**113,332**	**3,68%**

[d] Cereal straw share in Frankfurt Rhine-Main has been estimated by extrapolating the cereal straw share in the states of Hesse, Rhineland-Palatinate, and Bavaria [41]: Wheat (54,13%), Barley (24,82%) and Corn (12,23%)

[e] Leaves share from agricultural waste in Germany is estimated to be mostly sugar-beet leaves [40].

[f] Organic waste from households has not been included in this study

The importance of identifying the feedstock share relies on the impact the composition has on the produced syngas composition and on the methanol potential. This is evident in the simulation results, where the moisture, ash, and hydrogen content of the biomass play a significant role.

4.2. E-methanol potential

The composition of biomass feedstock is a critical determinant of bio-methanol yield, as physical and chemical properties directly influence conversion efficiency. Figure 3 presents the bio-methanol yield generated from the available biomass resources in the selected locations.

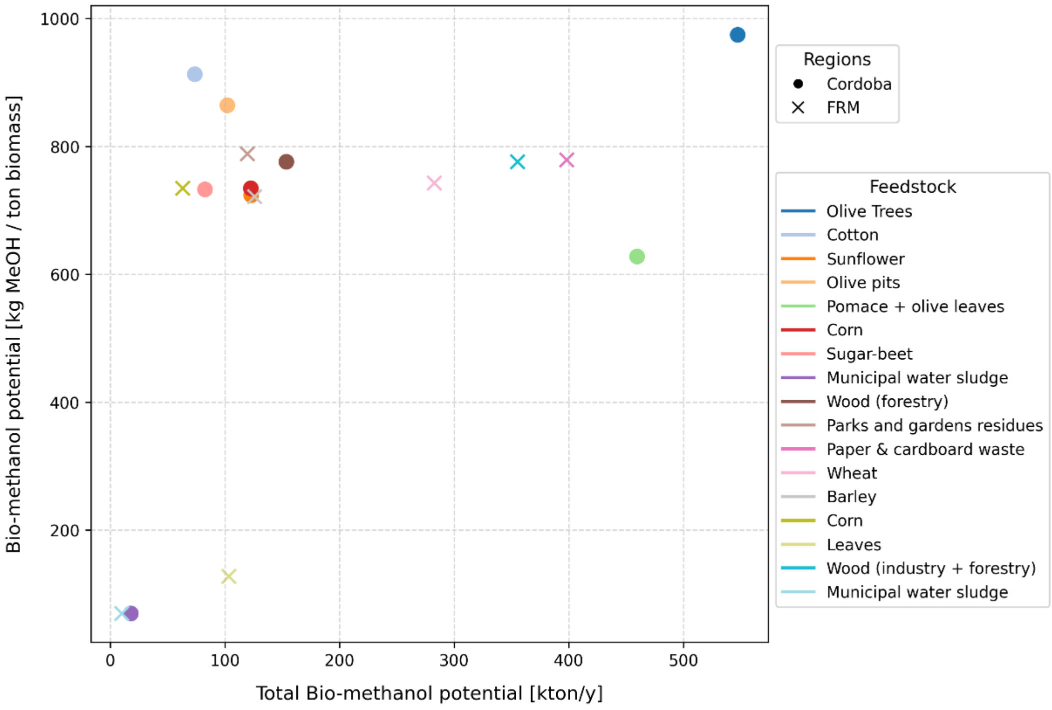

Figure 3. Bio-methanol yield based on feedstock type in the selected locations

High moisture content, typical of feedstocks like municipal sewage sludge or leaves, requires an energy-intensive pre-drying stage; this not only increases operational costs but also reduces the net volume of biomass available for the gasification process. Conversely, feedstocks with high hydrogen concentrations significantly enhance methanol synthesis. A prime example is olive tree biomass, which presents high specific and total methanol yield, due to the abundance of this resource in the province of Córdoba.

As illustrated in **Figure 4**, e-methanol potential in the Frankfurt Rhine-Main (FRM) region significantly exceeds that of Córdoba due to the stark difference in industrial CO_2 availability.

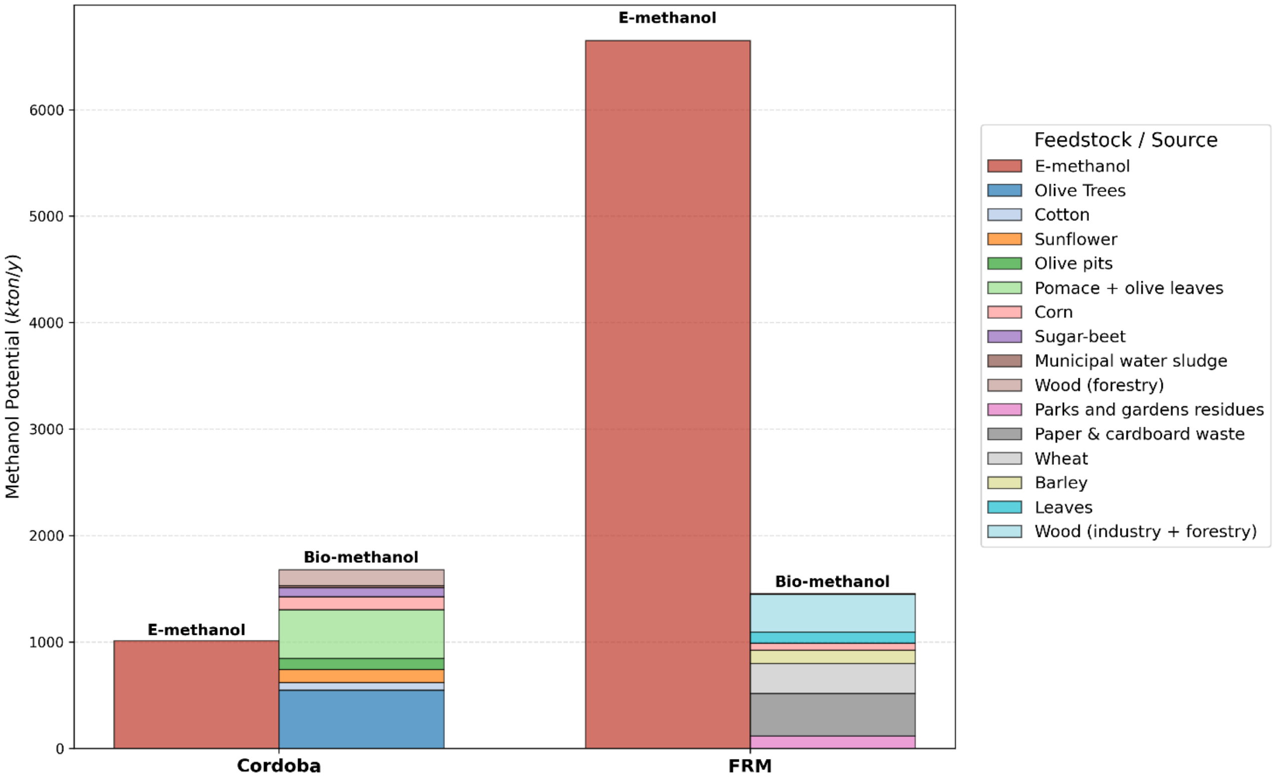

Figure 4. *Green methanol potential in the selected regions*

While Córdoba accounts for vast solar resources, the scarcity of industrial emissions suitable for CCU systems severely constrains local production. To address this supply gap, CO_2 would need to be transported from external regions - a logistical requirement that increases costs and reduces the area's strategic potential for e-methanol production. Conversely, the FRM region serves as one of Germany's primary industrial hubs; here, e-methanol potential is not limited by carbon availability but rather by the further development and integration of renewable energy sources such as wind and solar.

4.3. Energy and resources

Approximately 96.6% to 99% of the total energy required for e-methanol synthesis is consumed during the electrolysis stage, with the remaining balance allocated to the compression of hydrogen and carbon dioxide. The specific case study in which this energy demand is met exclusively through photovoltaic (PV) sources is illustrated in **Figure 5**. The overall production capacity is constrained by the availability of industrial CO_2 emissions.

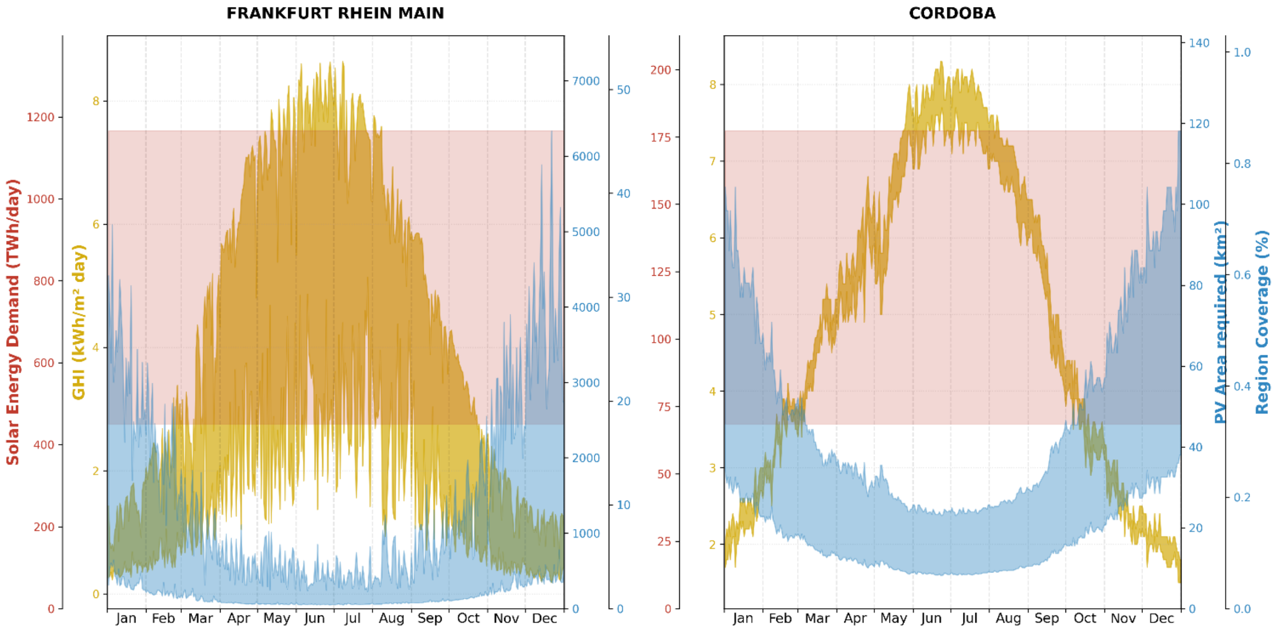

Figure 5. *PV installation strategy to satisfy the e-methanol production energy requirements*

As illustrated by the data, the solar energy demand in the Frankfurt Rhine-Main (FRM) region is significantly higher, driven by the vast potential for industrial CO_2 utilisation. Under a worst-case scenario - defined by the lower bounds of electrolysis and photovoltaic (PV) efficiency - the required solar PV panels installation would occupy up to 42,9% of the region's total land area. While the consistent solar profile in Córdoba is technically ideal, viable e-methanol production relies on the duality of both carbon feedstock and energy resources. Consequently, despite the region’s optimal renewable availability, the deficiency in industrial emissions remains a critical bottleneck that hinders its overall e-fuel potential.

Regarding bio-methanol, beyond fuel yield, the specific composition of the biomass feedstock also significantly influences the overall electrical and thermal power consumption of the bio-methanol production process (**Figure 6**). The correlation between both is linear and the deviation is typically low for most feedstock types (under 2.1%). ‘Electrical power consumption’ covers the power demand of compressors, whereas ‘thermal power consumption’ includes a wider variety of units, such as heaters, reactors, and distillation columns. Optimal heat recovery strategies could leverage the ‘waste heat’ available from the cooler outputs and the exothermic methanol synthesis reactor.

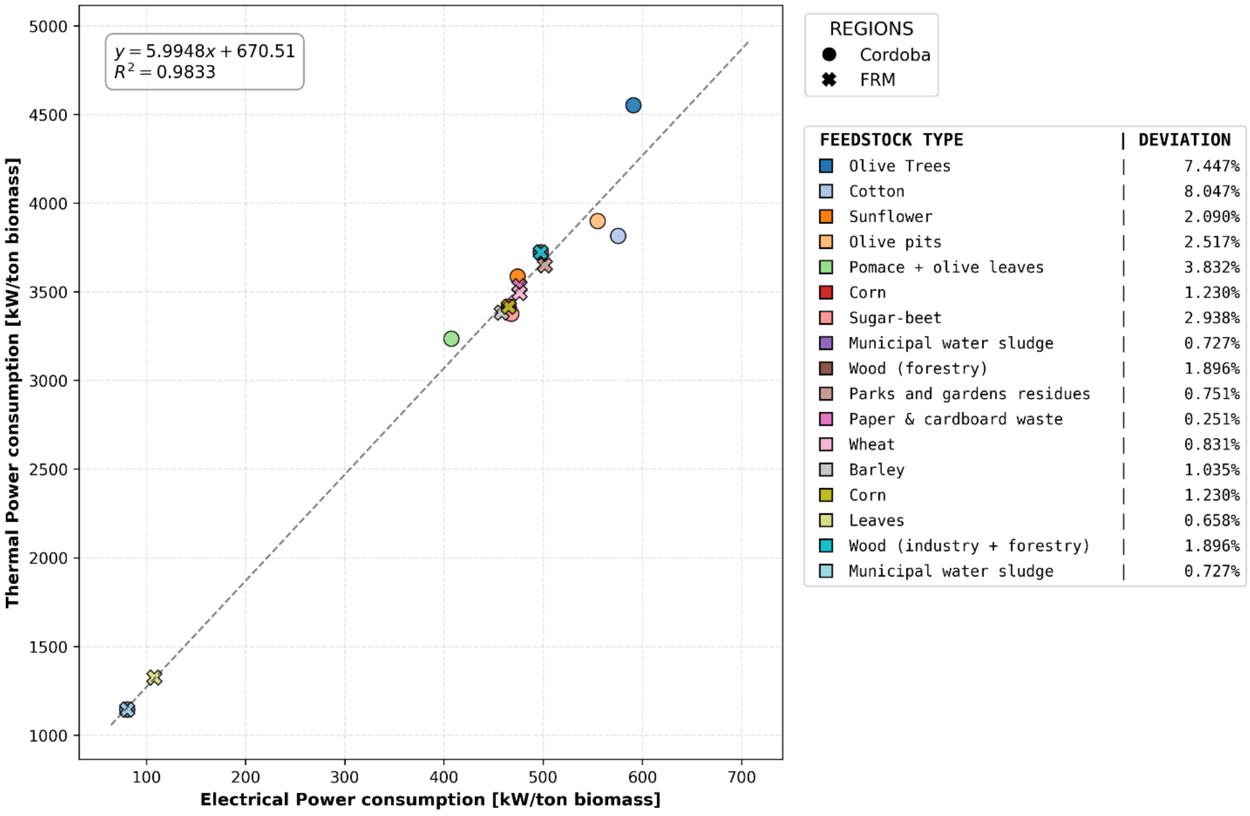

***Figure 6**. Bio-methanol electrical and thermal energy consumption trendline and corresponding deviation*

The moisture content of the feedstock plays a dual influence on the system's energy profile. While high moisture levels necessitate a more intensive drying process - thereby increasing initial energy demand - they also effectively reduce the volume of "dry" or pure biomass available for the subsequent gasification stage. Paradoxically, this can lead to lower energy consumption (and lower yield) during the gasification phase itself, as the reactant rate is defficient.

Regarding the thermal energy balance, although the drying and gasification stages are energy-intensive, the system offers significant potential for heat integration. By implementing thermal recovery strategies, waste heat generated during the process can be captured and repurposed for process heating, optimising the plant's efficiency.

4.4. Economic assessment

Literature reports higher investment costs for e-methanol production facilities than bio-methanol ones, with a fixed capital investment ranging from 247 to 289 M€ for 166.667 t/y [42]. Green hydrogen production represents the higher cost of e-methanol production, ranging from 60 to 97% of the total product cost [43], with electrolyser capital investment being 34-39% of the total plant cost [42]. OPEX is also dominated by the cost of electrolyser replacement. Total scaled investment cost was found to be 13% lower for bio-methanol plants (91.8 M€ to 80.1 M€ for a capacity of 166.667 t/y) [44]. In this case, the largest cost component for e-methanol is gas compression (52,2 M€), whereas for bio-methanol the highest cost is syngas cleaning (26,8 M€).

Assuming a USD to euro equivalency of 1 to 0.85, current e-methanol levelized cost of fuel (LCOF) is estimated between 678-1.356 €/t [45], with other more optimistic reports stating 560-615 €/t [42] and 517-972 €/t [46]. These values are expected to decrease down to 212-534 €/t by 2050, becoming competitive in the market with other solutions at current higher TRL, like fuel-based methanol, currently at 82-212 €/t [45]. On the other hand, the cost of bio-methanol is currently between 271- 653 €/t, with an expected reduction down to 186-475 €/t [45]. Other studies report higher costs, ranging from 822-1.057 €/t [46].

5. Conclusions

This study analyses the optimal pathways for renewable methanol production in Europe, demonstrating that it is highly dependent on regional resources. The comparative analysis between the studied locations reveals distinct techno-economic strategies for decarbonization.

Bio-methanol is currently the more economically competitive route, with costs as low as 271 €/t. It is particularly viable in rural, biomass-rich regions like Córdoba, where olive trees provide high hydrogen content and superior yields, together with other available feedstocks. However, effective biomass utilisation requires a thorough characterisation of the feedstock composition. This is essential to align the process design and technology with specific feedstock characteristics, ensuring maximised methanol yields and optimised energy efficiency.

E-methanol potential is strictly governed by the dependence on the duality of resources. While Córdoba offers optimal solar irradiance, it is constrained by low industrial CO_2 emissions due to the area's limited industrial infrastructure, creating a supply gap that reduces economic viability. Conversely, the FRM region's dense industrial hub enables massive e-methanol scaling, though this introduces significant land-use challenges, requiring up to 42.9% of regional surface area for PV installations in worst-case efficiency scenarios, to decarbonise the whole industrial sector.

While e-methanol costs are projected to become competitive by 2050 (212–534 €/t), bio-methanol remains the strategic choice for immediate deployment in agricultural regions. A diversified European policy that promotes e-methanol in industrial clusters and bio-methanol in rural areas will minimise logistical costs and accelerate the transition toward a carbon-neutral industrial sector.

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Nomenclature

CO2: Carbon dioxide

CCU: Carbon Capture and Utilisation

DAC: Direct Air Capture

FRM: Frankfurt Rhine-Main

LCOF: Levelized cost of fuel

PV: Photovoltaic

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