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Economic appraisal of Power-to-Liquid Fischer-Tropsch plants exploiting renewable electricity, green hydrogen, and CO_2 from biogas in Europe

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Abstract. The present work analyses the techno-economic potential of Power-to-Liquid routes to synthesize Fischer-Tropsch paraffin waxes for the chemical sector. The Fischer-Tropsch production unit is supplied with hydrogen produced by electrolysis and CO_2 from biogas upgrading. In the analysis, 17 preferential locations were identified in Germany and Italy, where a flow of 1 t/h of carbon dioxide was ensured. For each location, the available flow of CO_2 and the capacity factors for both wind and solar PV were estimated. A metaheuristic-based approach was used to identify the cost-optimal process design of the proposed system. Accordingly, the sizes of the hydrogen storage, electrolyzer, PV field, and wind park were evaluated. The analysis studied the possibility of having different percentage of electricity coming from the electric grid, going from full-grid to full-RES configurations. Results show that the lowest cost of Fischer-Tropsch wax production is 6.00 €/kg at full-grid operation and 25.1 €/kg for the full-RES solution. Wind availability has a key role in lowering the wax cost.

1 Introduction

To reduce the impact of climate change derived from human activities, several solutions are being proposed and studied with different levels of maturity at international level. In this context, the reduction of carbon dioxide (CO_2) emissions towards the environment, together with a rise in the installation of renewable energy and the deployment of innovative technologies are paramount to reach such a goal [1]. Accordingly, the International Energy Agency (IEA) has proposed a possible pathway for the implementation of different technologies to reach carbon neutrality in various industrial sectors by the year 2050 [2]. Power-to-X (PtX) and carbon capture and utilization (CCU) routes have been identified as crucial solutions.

Power-to-X routes combine several technologies to deliver the product "X", exploiting renewable energy sources (RES). Such pathways involve hydrogen obtained through electrolysis fed with RES (i.e., green hydrogen). H_2 can be further mixed with CO_2 to promote carbon dioxide utilization and synthesize non-fossil marketable compounds. In this regard, Power-to-Liquid solutions aiming at Fischer-Tropsch (FT) favour the generation of carbon-neutral hydrocarbons to decarbonize the heavy transport and chemical sector with a single application [3]. While the decarbonization of the transport sector has been widely investigated, the decarbonization of the chemical sector is non-trivial, with the FT being one of the few technologies that allows producing long-chain hydrocarbons (i.e., paraffin waxes) destined to the chemical sector [4]. Additionally, a rise in the demand for such products is forecasted, with a market expansion from 5.1 billion € in 2018 to 7.5 billion € in 2025 [5]. However, at the current date, no alternative-to-fossil commercial production for these compounds is available.

Parallelly, there exists a high availability of biogas plants (i.e., anaerobic digestors) installed in Europe, with a growing trend in the installation of upgrading facilities to obtain biomethane (for gas grid injection) and carbon dioxide (which is typically vented to the atmosphere). Thus, there is a large amount of potential carbon dioxide that can be utilized to generate further products and makes it advantageous to study solutions that use biogas-derived CO_2 [6].

Moreover, RES-based solutions involving the production of FT material are seldom found in literature [7], with none found dedicated to the waxes production. However, given the wide range of products generated by the FT technology, it becomes relevant to investigate solutions that involve such a technology fed by RES to decarbonize several sectors at once.

Accordingly, the present work analyses Power-to-Liquid routes installed in Europe to synthesize FT paraffin waxes destined to the chemical sector. More in detail, it studies routes that combine renewable energy production (wind and/or solar power), green hydrogen generation via low temperature electrolysis, hydrogen storage, and FT product generation with CO_2 coming from anaerobic digestion processes (Fig 1). Such routes are being

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investigated ranging from full-grid to full-RES conditions, with cost-optimal economic considerations on the cost of FT waxes production.

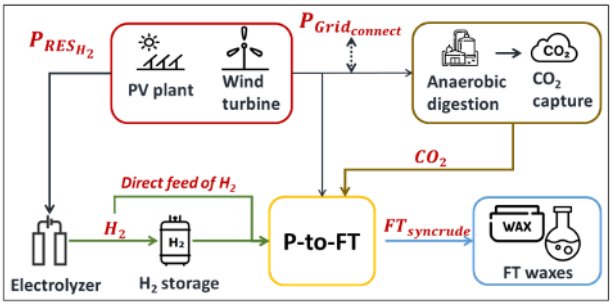

Fig. 1. Schematic of the plant investigated in this analysis.

2 Methodology

17 preferential locations were identified throughout Germany and Italy (12 in Germany, 5 in Italy), the two European countries with the largest number of installed biogas plants. Each of the selected sites presents an anaerobic digester with an installed biogas upgrading unit that provides a flow of clean CO_2 equal to or higher than 1000 kg/h [8]. This CO_2 flow threshold was set based on previous results obtained for a CCU plant converting CO_2 from biogas into FT hydrocarbons with relevant industrial size [9]. Geographical locations are shown in Fig. 2.

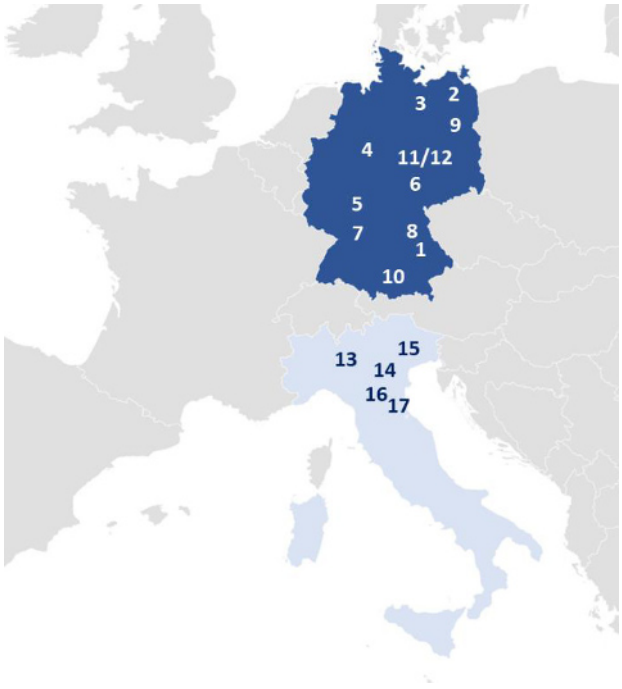

Fig. 2. Locations used in the present analysis, where an anaerobic digestor is present, with an existing biogas upgrading unit with a minimum flow of CO_2 of 1 t/h.

For each location, the availability of CO_2 was estimated. Similarly, the potential production of renewable electricity was evaluated, and capacity factors (CF) for both wind and solar PV were derived exploiting yearly profiles of irradiance and wind speed data taken from the online PVGIS tool [10]. The wind turbine corresponded to model v27 from Vestas producer [11]. Wind speed data were corrected to the turbine height of 30 m. CO_2 flow and capacity factor for each location are listed in Table 1. Locations in Germany present a higher availability of wind energy compared to Italy, but lower PV capacity factors.

Table 1. Wind and PV capacity factors and carbon dioxide evaluated for each investigated location.

State	Code	Location	CO_2 flow	Wind CF	PV CF
			[t/h]	[%]	[%]
DE	1	Aiterhofen Niederbayern	1.35	2.71%	11.39%
DE	2	Dargun	1.54	11.23%	11.43%
DE	3	Güstrow	6.34	10.52%	11.06%
DE	4	Horn Bad Meinberg	1.38	4.60%	10.02%
DE	5	Industriepark Hoechst	1.04	5.92%	10.92%
DE	6	Könnern 2	2.28	5.18%	11.55%
DE	7	Schwaigern	1.23	4.06%	11.61%
DE	8	Schwandorf	1.35	3.72%	11.57%
DE	9	Schwedt	3.8	5.12%	11.36%
DE	10	Wolnzach	1.36	3.01%	11.32%
DE	11	Zörbig 1	3.8	5.18%	11.57%
DE	12	Zörbig 2	3.14	5.18%	11.57%
IT	13	Montello	2.62	0.92%	12.90%
IT	14	Este	2.62	1.48%	14.99%
IT	15	Maniago	3.93	0.18%	12.55%
IT	16	Faenza	4.91	0.09%	10.41%
IT	17	Sant'Agata Bolognese	1.12	0.71%	14.85%

2.2 System optimization

Employing PV/Wind producibility data, the analysis utilized an optimization model based on a metaheuristic algorithm to identify the cost-optimal design of the system. More specifically, this model (adapted from Ref. [12]), employs the particle swarm optimization (PSO) algorithm to determine the system configuration that allows a certain objective function (OF) to be minimized. In this work, the wax cost was considered as OF to perform the optimal design (i.e., Eq. 3). Hence, the sizes of the hydrogen storage, alkaline electrolyzer, PV field, and wind farm were evaluated.

All the CO_2 available at each site was exploited, and the H_2-storage guaranteed a constant flow of hydrogen needed by the FT reactor when its direct production was

not doable from the electrolyser. Additionally, in case of extra hydrogen produced by the electrolyser, this was stored in the storage unit until reaching its maximum capacity. Electric energy generated by RES was fed to the CCU plant and electrolyser for hydrogen generation. Extra RES was curtailed to the grid once the storage was full, and the hydrogen load covered. The system was grid-connected, to allow for the sale of curtailed renewable electricity not utilized by the system, or to buy electricity when RES power was not available or not investigated (e.g., 100% grid connection configuration). An electrolyser efficiency of 51 kWh/kg_{h2} was considered [13]. Moreover, the electrolyser operation was set to null when its input power was lower than 15% of its nominal power [13].

The CCU-to-FT section operated at steady-state conditions for constant output of FT compounds, utilizing a reverse water gas shift (RWGS) reactor for the generation of syngas followed by a Co-based FT reactor and FT products distillation into naphtha (C_5-C_{11}), middle distillates (C_{11}-C_{20}), and waxes (C_{20+}). FT gas fraction was internally recirculated. At the reference size of 1 t/h of CO_2 at the inlet of the CCU plant, 79.9 kg/h, 93.7 kg/h and 85.7 kg/h of naphtha, middle distillates and waxes were produced, respectively. A detailed description of the CCU-to-FT plant together with an energy analysis can be found at [9,14]. The FT synthesis accounted for a carbide mechanistic kinetic model for the description of the FT products generation [15].

For each location, sensitivities on the fraction of electricity coming from the grid were accounted for while estimating the waxes cost. Hence, the cost-optimal system composition was studied ranging from full-grid to full-RES configurations. The full-RES solution was assumed to be connected to the electric grid only to sale the curtailed RES.

2.3 Economic analysis

Based on CAPEX, OPEX, and revenues values, the wax production cost was evaluated for each site and for different scenarios with rising levels of RES exploitation. The annuity method was utilized, with a plant life of 25 years (N_{rt}) and a weight average cost of capital (WACC) of 4.0% in the baseline configuration. Accordingly, the wax production cost (in €/kg_{wax}) was obtained as follows:

$$TIC_{inv}=(\sum C_{P,i}) (1+f_{site}) (1+f_{cont}+f_{eng}) (1+f_{com}) \quad (1)$$

$$CAPEX_{ANN}=TIC_{inv} (WACC (1+WACC)^(N_{rt}))/ ((1+WACC)^(N_{rt})]-1) \quad (2)$$

$$\text{Wax cost}=(CAPEX_{ANN}+C_{OP}-\text{Revenues})/(\text{FT Wax Production Rate}) \quad (3)$$

Where TIC_{inv} (in €) is the total investment cost and $C_{P,i}$ (in €) is the purchase cost of the i-th component (see Table 2). The f_j parameters account for site preparation (0.2), contingencies (0.2), engineering (0.1) and commissioning (0.1) costs. $CAPEX_{ANN}$ was derived by correcting TIC_{inv} by the annuity coefficient.

OPEX costs (C_{OP}, in €/y) included the yearly sum of operation and maintenance, labour cost, electricity costs, catalysts replacements, components replacement (e.g., electrolysers), and raw material costs (e.g., water, biogas). Revenues accounted for the sale of by-product oxygen from electrolysis, curtailed electricity, naphtha, and middle distillate, and credits from the sale of biomethane to the gas grid. BioCH_4 credits were included for the injection of biomethane into the gas grid:

- German policies, bioCH_4 sale price of 31.6 €/kWh with 20 years sale credits for 61.6 €/MWh [16–18];
- Italian policies, sale price of CH_4 of 20.9 €/kWh, with credits of 62.7 €/MWh for 10 years and 0.305 €/m^3 for each subsequent year [16,19].

Baseline electricity was purchased at 100 €/MWh and sold at 80 €/MWh [20]. Other relevant costs are listed in Table 2 and Table 3.

Table 2. Cost used for CAPEX evaluation.

System	Investment cost	Ref.
PV power plant	800 €/kW	[21]
Wind power plant	1100 €/kW	[22]
Electrolyser	$1437 Palk_{nom}^{-0.095}$ €/kW	[14]
H_2 Storage	470 €/kg	[23]
CCU (Biogas up.+RWGS+FT)	8878.2 k€/(t_{CO2}/h)	[14,24]

Table 3. OPEX and revenues costs used in the analysis.

Cost item	Value	Ref.
O&M	3% TIC (€/y)	[25]
PV Repl.	80 €/kW (10 y)	[26]
Electrolyser Repl.	26.6% Elect Inv. Cost (9 y)	[27]
Biogas	50 / 44.3 €/MWh (DE / IT)	[16,17,19]
Water	2 €/m^3	[28]
Labour	49500 / 75000 €/Op/y*4 operators (IT / DE)	[14]
Cat. Repl.	1% CCU Inv. Cost (3 y)	[14]
O_2 sale	0.15 €/kg	[29,30]
Naphtha sale	0.31 €/l	[31]
Midd. Dist sale	0.60 €/l	[32]

3 Results and discussion

3.1. Grid connection effect

For each location, the cost of FT wax production was evaluated, by varying the share of grid electricity from 0%

to 100%. The resulting Pareto fronts for all the 17 locations are reported in Fig. 3. It can be noted that the wax cost increases as direct RES electricity is used, with an almost constant wax cost in the range 75% to 100% of electricity from the grid. Accordingly, bigger sizes of PV, wind, H_2-storage, and electrolysers are needed to sustain the system operation when increasing the share of electricity from local RES.

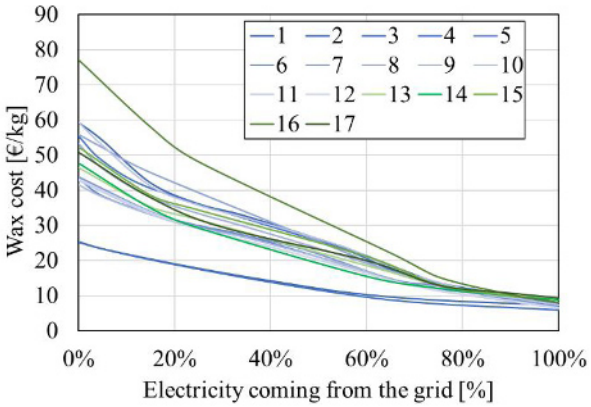

Fig. 3. Cost of FT wax at different grid connection values.

For the sake of comparison, the wax costs for the full-grid and full-RES cases are graphically displayed in Fig. 4. With 100% electricity from the grid, all the locations provide a cost of wax production lower than 10 €/kg. Moreover, the most economic locations in Germany and Italy correspond to Güstrow (6.00 €/kw_{wax}) and Montello (8.05 €/kw_{wax}), respectively. However, electricity coming from the grid might not be of renewable source, increasing the carbon footprint of the generated products. In this regard, a solution with 0% grid electricity utilization (i.e., full-RES configuration) ensures only green energy consumption. Due to the installation of PV, wind, and H_2-storage units, the rise in the wax cost ranges from 254% to 857%, with the two most economically feasible solutions corresponding to Dargun and Güstrow, in Germany. Moreover, it is to note that the cost of wax production is poorly affected by the amount of carbon dioxide entering the unit, and the main key factor is the percentage of grid electricity purchased. Accordingly, Dargun has flow of carbon dioxide of 1.54 t/h, while Güstrow presents 6.34 t/h of CO_2. And they reach similar costs of waxes at full-RES operation (25.44 €/kg and 25.12 €/kg, respectively). With 100% grid electricity, the difference in cost of waxes between the two locations becomes more remarkable, with values of 7.18 for Dargun and 6.00 €/kg Güstrow.

Concerning the optimal sizes of the different components, Table 4 lists the cost-optimal values of the full-grid and full-RES scenarios for all the locations. The resulting production of FT products is instead presented in Fig. 5. Expectedly, locations with high CO_2 availability result in high FT products generation. Moreover, with 100% electricity from the grid, the only component required in addition to the CCU unit is the electrolyser. For full-RES operation, all the other components (i.e., PV, wind and hydrogen storage) become relevant.

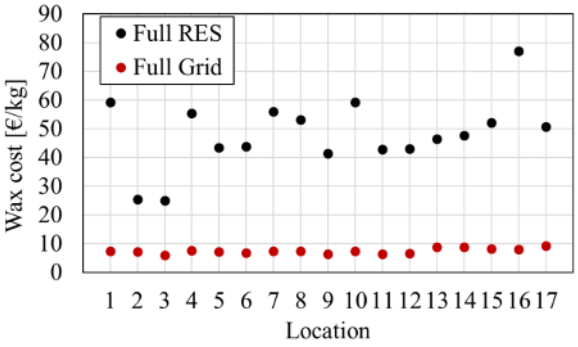

Fig. 4. Wax production cost for the full-grid and full-RES cases.

Table 4. Components size and wax cost at each location.

Code	Grid	Wax	PV	Wind	Alk	H_2 Storage
	[%]	€/kg	MW	MW	MW	MWh
1	100	7.3	0.0	0.0	9.2	0.0
	0	59.3	87.7	101	32.8	9503.8
2	100	7.2	0.0	0.0	10.5	0.0
	0	25.4	24.6	199	21.5	1989.1
3	100	6.0	0.0	0.0	43.3	0.0
	0	25.1	115.4	735	98.6	8234.8
4	100	7.6	0.0	0.0	7.1	0.0
	0	55.4	46.3	147	21.3	5680.3
5	100	7.3	0.0	0.0	9.4	0.0
	0	43.4	44.0	201	28.5	3150.5
6	100	6.8	0.0	0.0	15.6	0.0
	0	43.8	78.4	310	46.7	6357.3
7	100	7.4	0.0	0.0	8.4	0.0
	0	56.0	55.3	140	26.1	8989.7
8	100	7.3	0.0	0.0	9.2	0.0
	0	53.2	63.0	150	28.5	7780.8
9	100	6.4	0.0	0.0	25.9	0.0
	0	41.5	113.0	517	77.7	10082.5
10	100	7.3	46.2	75	11.7	16.0
	0	59.3	84.3	115	31.6	9948.2
11	100	6.4	0.0	0.0	25.9	0.0
	0	42.9	130.3	517	76.4	10711.1
12	100	6.5	0.0	0.0	21.4	0.0
	0	43.1	109.6	411	63.8	9255.1
13	100	8.9	0.0	0.0	17.9	0.0
	0	46.4	181.7	0.0	72.7	10471.4
14	100	8.8	0.0	0.0	17.9	0.0
	0	47.7	156.4	0.0	68.0	18589.6
15	100	8.2	0.0	0.0	26.8	0.0
	0	52.3	285.3	0.0	105.1	27747.9
16	100	8.1	0.0	0.0	33.5	0.0
	0	77.1	461.6	0.0	148.9	73825.6
17	100	9.3	0.0	0.0	7.6	0.0
	0	50.8	68.8	0.0	28.8	8435.7

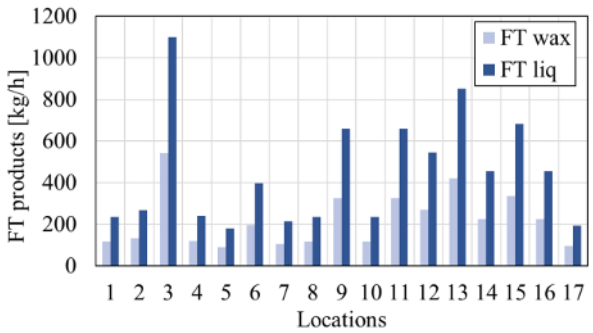

Fig. 5. FT products generation at each location.

3.2. Renewable energy capacity factor

For the various locations, a different capacity factor for wind and PV power is available. Accordingly, Fig. 6 shows the cost of waxes production at full-RES conditions together with the RES capacity factors. As a matter of fact, the PV capacity factor is similar for all the selected locations (range of 10 to 13%), while there exist a much higher variability considering the wind power capacity factor. In this regard, the selected Italian locations have low to null wind power availability. This results in zero MW of wind power installed for locations 13 to 17, with a consequent PV size to be installed very large (bigger than German locations). On the contrary, locations 2 and 3 have the highest availability of wind power, resulting in low cost of wax production. These results suggest that the implementation of these CCU-PtL plants – specifically aiming at FT waxes for the chemical sector – is more effective in locations where high wind power capacity factors are available.

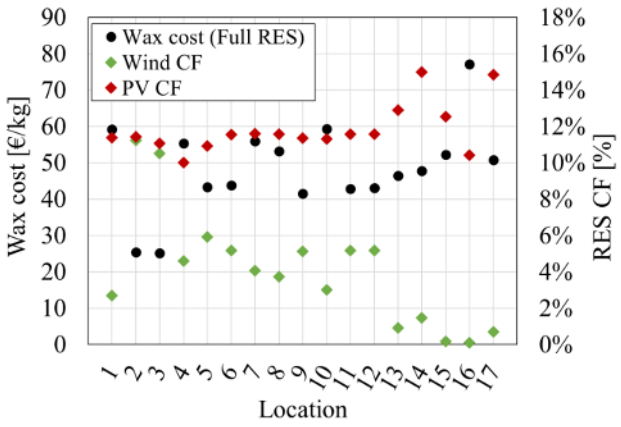

Fig. 6. Cost of wax production for the full-RES configuration against the wind and PV capacity factors.

3.3. Güstrow location

Specific results about system sizing are provided for the most performing location (Güstrow, DE), but similar results could be derived for all the 17 locations. Fig. 7 depicts the PV and wind power generation profiles over the year for Güstrow to ensure full-RES operation.

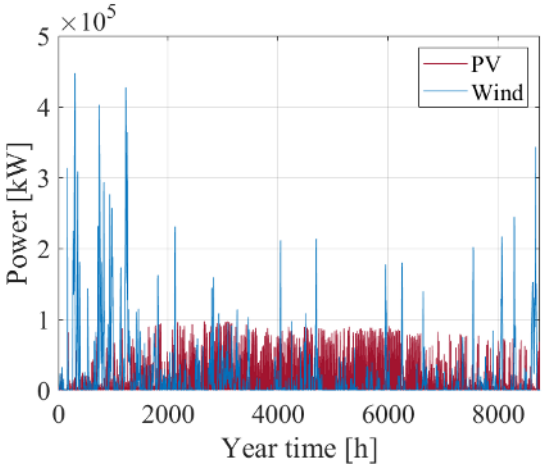

Fig. 7. PV and wind power for the full-RES configuration in Güstrow.

The TIC breakdown of the full-RES configuration is reported in Fig. 8. It can be observed that the green hydrogen production step (i.e., RES generators, electrolysis unit, and hydrogen storage) is the greatest contributor, accounting for around 97% of the TIC. Specifically, wind power represents the most impacting element (with about 74% of the CAPEX). This is connected to the need of having high-RES capacities to ensure a cost-effective full-RES solution.

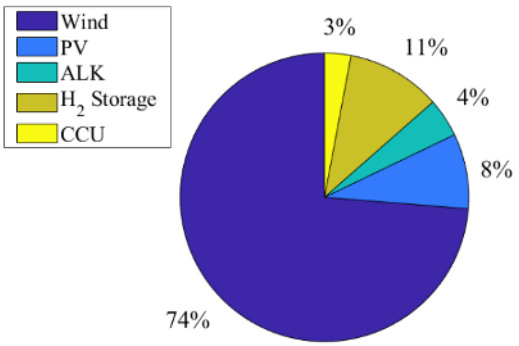

Fig. 8. CAPEX breakdown for the full-RES configuration in Güstrow.

It should be noted that the resulting wax cost of 25.12 €/kg is related to the full-RES case where the RES curtailment is sold to the electric grid. In the case of a completely off-grid system (i.e., no power exchanges with the grid) no extra RES can be sold to the grid. In this case, the wax cost would become 28.12 €/kg, which is slightly higher than the baseline case selling extra RES (the component sizes are around the same for the two options).

Additionally, further sensitivity analyses can be carried out. In this regard, economic parameters assumptions play a vital role in the evaluation of the cost of wax production. Accordingly, the WACC was varied from 2.0% to 10.0% at full-RES operation (i.e., 0% electricity from the grid). As visible from Fig. 9, more favourable conditions for the synthesis of waxes come at low WACC values. Such result is in line with literature studies involving PtX units [7]. Moreover, a compensation

derived by the utilization of CO_2 could be included. Accordingly, the German Power-to-X alliance has proposed an initial credit value of 300 €/kg of carbon dioxide utilized in PtX units [33]. With this credit, the reduction in cost of wax production would be of about 0.6 €/kg regardless of the WACC value.

Thus, to reach a breakthrough of such plant design to be competitive with the current fossil production route (2.50 €/kg_{wax}), credits higher than 300 €/kg of CO_2 would be needed. Alternatively, a solution with high grid electricity share for FT production could be preferential over the full-RES one, provided that the electricity used has a low carbon footprint. As shown before, the wax production cost would become lower at higher share of grid electricity. However, it is to point out that such processes involve technologies that are expected to have a reduction in their cost and operations (i.e., RES generators and electrolysers), and can impact the cost of heavy FT compounds. Lastly, complete decarbonization of the chemical sector would not be reached without FT long chain carbon-neutral hydrocarbons.

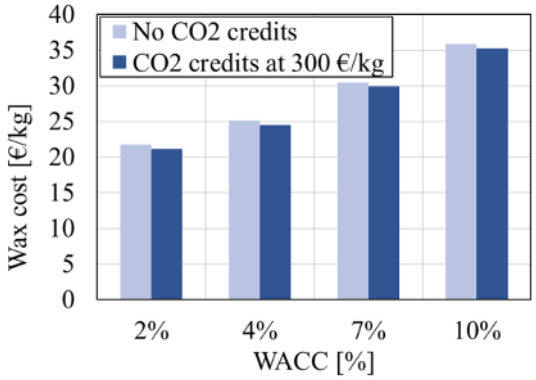

Fig. 9. Effect of WACC variation and carbon dioxide credits on the cost of wax production (full-RES configuration in Güstrow).

4 Conclusion

The present study investigates the production of FT compounds (i.e., liquid fuels and chemicals) with a focus on FT waxes destined to the chemical sector in a CCU and Power-to-Liquid framework. At current date, no alternative to fossil route is commercially available for these products. In this analysis, hydrogen from electrolysis and CO_2 separated from biogas are the material feedstocks for the FT production unit.

A cost-optimal optimization was performed in 17 locations in Europe, exploiting a flow of clean carbon dioxide available from the upgrading of biogas into biomethane. The optimal design of the wind and PV rated power, H_2-storage size, and electrolyser nominal power was carried out, with plant configurations ranging from 0% (full-RES) to 100% (full-grid) electricity from the grid. Accordingly, full-grid configurations have a cost of wax production (around 6 to 10 €/kw_{wax}) closer to the fossil route. However, full-RES solutions ensure having carbon neutral production of FT waxes. Lastly, the analysis shows that RES-based configurations require a high capacity factor of wind power generation, constraining the synthesis of FT waxes to places with high wind availability. In this regard, the analysis provides evidence of the convenience of installing these units in the north of Germany compared to Italy.

Further investigation will include the evaluation of optimal PV/wind power capacity factors to make the RES-based FT wax synthesis competitive with the fossil route. Suitable locations will be then identified as a support for decision makers to foster the complete decarbonization of chemical pathways.

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