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DEEP DECARBONIZATION: BECCS (P PATRIZIO AND N MAC DOWELL, SECTION EDITORS)

The Potential of Power and Biomass-to-X Systems in the Decarbonization Challenge: a Critical Review

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Abstract

Purpose of the Review The scope of this work is to present a critical review of the novel class of plants for the enhanced production of bioproducts in power and biomass-to-X (PBtX) plants, where the excess carbon in the feedstock is converted into a product thanks to the addition of hydrogen from water electrolysis, rather than being vented as CO_2.

Recent Findings The review of the recent literature shows that (i) a significant gain in carbon efficiency can be achieved with this class of plants compared to corresponding biomass-to-X plants; (ii) there is high dependency of the power-to-X efficiency on the efficiency of the electrolysis system and a relatively low dependency on the final product; and (iii) the economic competitivity of PBtX plants is closely associated to the cost of hydrogen (i.e., electrolysis capital cost, electricity cost, and capacity factor) and such systems cannot rely only on green hydrogen from the low expected amounts of excess electricity from intermittent renewables.

Summary In this work, through a simplified economic analysis, the region of competitiveness of this class of plants compared to other possible uses of biomass has been qualitatively identified. The research gaps mainly lie in the lack of assessments on the design and operating criteria of flexible PBtX plants and of studies providing insights on the value of flexibility for a PBtX plant, when integrated in the electric energy systems of the future.

Keywords Bio-fuel · Bio-hydrogen · BECCS · Power-to-X · CO_2 utilization · Flexibility

Introduction

Biomass is a unique resource of renewable energy and renewable carbon. The amount of biomass for use in the energy, transport, and chemical sectors is limited by the availability of land and by the competition with the food value chain. Therefore, it is of paramount importance to make the best use of the energy and the carbon in the biomass, according to the market and societal needs and to sustainability criteria [1, 2].

In the past decades, the relatively low value of carbon compared to energy was such that biomass has been mostly used for heat and power generation through combustion, with unrestricted emission of CO_2. This is likely to change in the next decades if the commitment of governments and the regulations in limiting the CO_2 concentration in the atmosphere is confirmed, that will lead to an increase of the biogenic carbon value. Also, the rise of solar and wind power generation will likely cause a reduction of the average electricity prices and an increased value of the services to improve the resiliency of the electric energy system through energy storage and flexible power generation.

In this context, understanding the best use of biomass depending on the regional energy mix [3] and on the market and regulatory conditions is a strategic issue for industry and policymakers. The possible uses of biomass include the following:

i. combustion for power and heat generation, with or without CO_2 capture and storage;
ii. conversion into a carbon-based product (e.g., methane, methanol, Fischer-Tropsch fuels) for the transport sec-

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tor or the chemical industry, with or without capture and storage of the excess CO_2;

iii. conversion into a carbon-based product, with enhanced productivity through the conversion of the excess carbon with added green hydrogen in a power and biomass-to-X system;

iv. production of bio-hydrogen, with or without CO_2 capture and storage;

v. production of biochar and other products (e.g., power, liquids, hydrogen).

When integrated into the broader energy system, plants need to deal with the variable price of electricity that varies on hourly time-scales due to the intermittent solar and wind power generation, and of CO_2, hydrogen, and carbon-based products that may vary on weekly–monthly time scales depending on the respective markets. Therefore, the expected time-dependent relative value of power, carbon-based products, hydrogen, and sequestered CO_2 may lead to the development of multi-product plants, to be operated flexibly in order to produce the good(s) with the highest added value.

This work focuses on plants for the conversion of second-generation biomass into liquid products via gasification-based pathways shown in Fig. 1:

a. biomass-to-X, with emission of the excess CO_2 (BtX);
b. power and biomass-to-X, with reduced CO_2 emission and increased productivity thanks to green hydrogen addition (PBtX);
c. biomass-to-X, with capture and storage of the excess CO_2 (BtX CCS).

The aims of this paper are as follows: (i) to present a review of the recent literature on the relatively novel concept of power and biomass-to-X plants, (ii) to provide insights on the conditions that make these plants economically competitive compared to other biomass conversion pathways, and (iii) to provide inputs to stimulate research on flexible power and biomass-to-X.

Critical Analysis of the Recent Literature on Power and Biomass-to-X

In Table 1, a summary of selected scientific works on power and biomass-to-X (PBtX) plants is reported, considering synthetic natural gas (SNG), methanol (M), gasoline (G) via methanol-to-gasoline process, dimethyl ether (DME), Fischer–Tropsch liquids (FT), and jet fuel (JF) as final products. The main key performance indicators are reported, referring to the carbon utilization efficiency, the power-to-X (PtX), and hydrogen-to-X (HtX) energy efficiencies and to

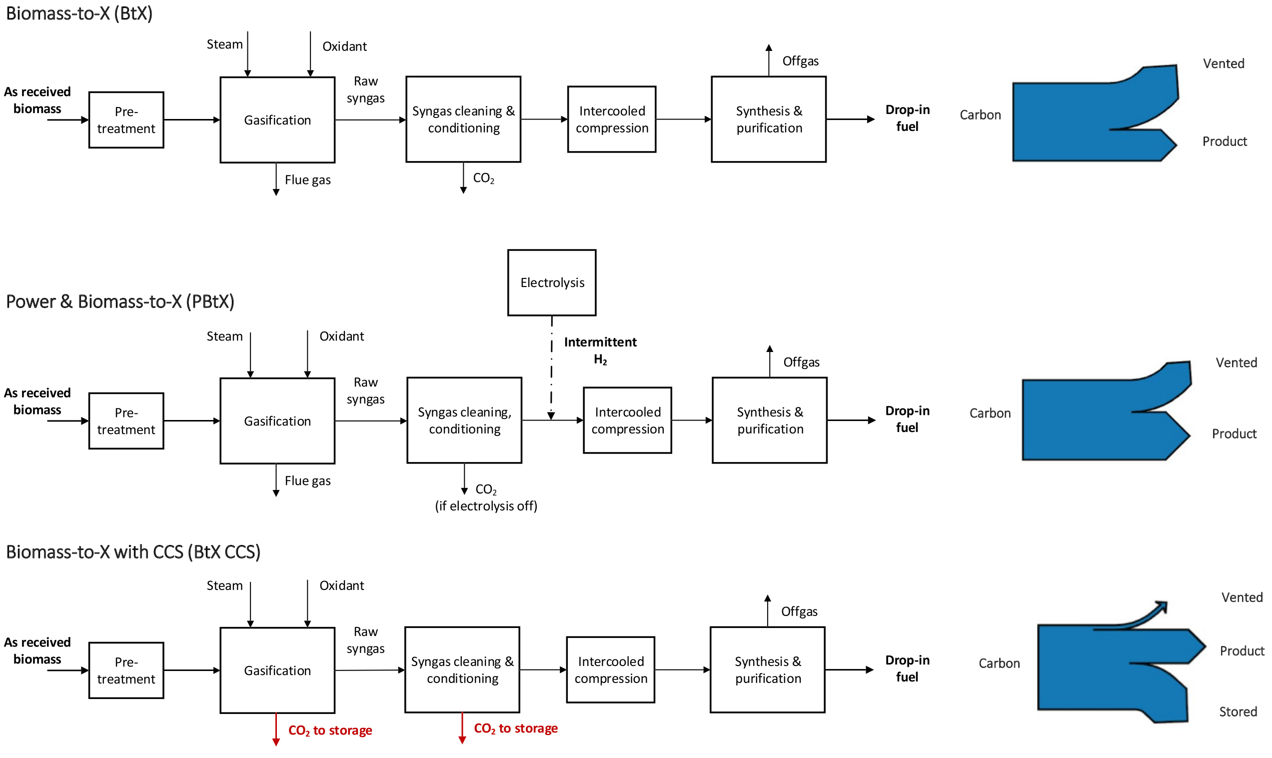

Fig. 1 Biomass conversion pathways via gasification and corresponding qualitative destination of the carbon

Table 1 Summary of the selected recent literature on PBtX studies. Values in italics have been derived from the data in the papers. When not present in the reference, properties of fuel mixtures (e.g., LHV, density) are taken from [9]. When necessary, the 2019 conversion $/€ equal to 1.12 has been applied

Reference	Biomass input, gasification and syngas cleaning, and conditioning technology	Electrolyser technology and power to LHV efficiency	Biofuel produced	Carbon efficiency	PtX efficiency	HtX efficiency	Main data for economic analysis	Cost of product
[4••]	Biomass input: 100 MW, 50%wt moisture O_2-blown fluidized bed gasification, syngas reforming, WGS reactor (bypassed in PBtX operation), CO_2 separation	Alkaline η = 62%	M, SNG, G	BtX: *37.5%* (M) *32.2%* (G) *33.1%* (SNG) PBtX: *48.9%* (M) *42.1%* (G) *49.8%* (SNG)	*51.7%* (M) *44.6%* (G) *51.1%* (SNG)	*84.7%* (M) *73.1%* (G) *82.3%* (SNG)	Electrolysis cost: 589 €/kW (M) 571 €/kW (G) 565 €/kW (SNG) Electricity price: 50.4 €/MWh Capacity factor: 91% (8000 h/y) Biomass cost: 5 €/GJ TCI PBtX (per kW_{prod})^1: 2320 €/kW (M) 3050 €/kW (G) 1925 €/kW (SNG) TCI BtX (per kW_{prod})^1: 2335 €/kW (M) 3055 €/kW (G) 2000 €/kW (SNG)	PBtX: 24.4 €/GJ (M) 27.6 €/GJ (G) 22.7 €/GJ (SNG) BtX: 20.6 €/GJ (M) 22.6 €/GJ (G) 17.7 €/GJ (SNG) e-product: *36.9 €/GJ* (M) *44.0 €/GJ* (G) *32.6 €/GJ* (SNG)
[4••]	CO_2 as carbon source, direct CO_2 hydrogenation	Alkaline η = 62%	M, SNG, G	PtX: *95.0%* (M) *81.7%* (G) ~ *100%* (SNG)	*51.5%* (M) *44.6%* (G) *51.1%* (SNG)	*84.4%* (M) *73.1%* (G) *82.3%* (SNG)	Electrolysis cost: 525 €/kW (M) 520 €/kW (G) 524 €/kW (SNG) Electricity price: 50.4 €/MWh Capacity factor: 91% (8000 h/y) CO_2 cost: 40 €/t TCI (per kW_{prod})^1: 1885 €/kW (M) 2615 €/kW (G) 1815 €/kW (SNG)	PtX: 40.0 €/GJ (M) 48.0 €/GJ (G) 36.8 €/GJ (SNG)

Table 1 (continued)

Reference	Biomass input, gasification and syngas cleaning, and conditioning technology	Electrolyser technology and power to LHV efficiency	Biofuel produced	Carbon efficiency	PtX efficiency	HtX efficiency	Main data for economic analysis	Cost of product
[5••]	Biomass input: 100 MW, 50%wt moisture O_2-blown fluidized bed gasification, syngas reforming WGS reactor and CO_2 separation only in BtX configuration	Alkaline, η = 67%	G, SNG	BtX: 30.5% (G) 32.5% (SNG) PBtX: 79.4% (G) 98.0% (SNG)	*48.4%* (G) *55.1%* (SNG)	*72.2%* (G) *82.3%* (SNG)	Electrolysis cost: 1000 €/kW Breakeven electricity price[2]: 35.4 €/MWh (G) 27.7 €/MWh (SNG) Capacity factor: 91% (8000 h/y) Biomass cost: 5 €/GJ TCI (per kW_{prod}): 2030 €/kW (G) 925 €/kW (SNG)	PBtX: 31.3 €/GJ (G) 21.4 €/GJ (SNG) BtX 31.3 €/GJ (G) 21.4 €/GJ (SNG)
[5••]	Biomass input: 100 MW, 50%wt moisture. Indirect dual fluidized bed steam gasification, syngas reforming WGS reactor and CO_2 separation only in BtX configuration	Alkaline, η = 67%	G, SNG	BtX: 28.8% (G) 31.4% (SNG) PBtX: 58.4% (G) 67.0% (SNG)	*49.7%* (G) *55.0%* (SNG)	*74.2%* (G) *82.1%* (SNG)	Electrolysis cost: 1000 €/kW Breakeven electricity price[2]: 33.9 €/MWh (G) 25.1 €/MWh (SNG) Capacity factor: 91% (8000 h/y) Biomass cost: 5 €/GJ TCI (per kW_{prod}): 2551 €/kW (G) 1287 €/kW (SNG)	PBtX: 30.4 €/GJ (G) 20.4 €/GJ (SNG) BtX 30.4 €/GJ (G) 20.4 €/GJ (SNG)
[6••]	Biomass input: 98.3 MW, 10%wt moisture. Pyrolysis + entrained flow O_2-blown gasification, WGS and CO_2 separation (BtX), or rWGS (PBtX)	PEM η = 69.2%	FT	BtX: 24.9% PBtX: 97.7%	*58.2%*	*83.1%*	Electrolysis cost: 942 €/kW Electricity price: 105 €/MWh Capacity factor: 94% (8260 h/y) Biomass cost: 5.4 €/GJ TCI (per kW_{prod}): 5559 €/kW (PBtX) 11,071 €/kW (BtX)	PBtX: 67.2 €/GJ[3] 70.0 €/GJ BtX: 64.1 €/GJ[3] 73.1 €/GJ e-product: *68.3 2 €/GJ*[3] *68.9 €/GJ*

Table 1 (continued)

Reference	Biomass input, gasification and syngas cleaning, and conditioning technology	Electrolyser technology and power to LHV efficiency	Biofuel produced	Carbon efficiency	PtX efficiency	HtX efficiency	Main data for economic analysis	Cost of product
[6••]	CO_2 as carbon source rWGS	PEM $\eta = 69.2\%$	FT	PtX: 98%	*50.6%*	*73.1%*	Electrolysis cost: 942 €/kW Electricity price: 105 €/MWh Capacity factor: 94% (8260 h/y) CO_2 cost: 37.75 €/t TCI (per kW_{prod})^4: 5364 €/kW (small) 4963 €/kW (large)	PtX (small): 85.9 €/GJ^3 89.1 €/GJ PtX (large): 82.5 €/GJ^3 85.6 €/GJ
[7••]	Biomass input: 435 MW, 40%wt moisture. Torrefaction + entrained flow O_2-blown gasification, rWGS, CO_2 separation	SOEC $\eta = 95.3\%$	FT	BtX: 37.8% PBtX: 91.3%	*78.6%*	*82.4%*	Electrolysis cost: 892.9 €/kW Electricity price: 44.6 €/MWh Electrolysis CF: 89% (7800 h/y) Biomass cost: 3.6 €/GJ TCI (per kW_{prod}): *4212 €/kW* (PBtX) *6430 €/kW* (BtX)	PBtX: *45 €/GJ* BtX: *61.7 €/GJ* e-product: *33.2 €/GJ*
[8]	Biomass input: 60 MW, 4.8%wt moisture. Entrained flow O_2-blown gasification	SOEC $\eta =$ N/A	SNG, M, DME, JF	BtX: *27.7%* (SNG) *35.6%* (M) *36.1%* (DME) PBtX: *85.4%* (SNG) *85.9%* (M) *86.3%* (DME)	*75.3% (SNG)* *79.8%* (M) *81.8%* (DME) *68.3%* (JF)	N/A	Electrolysis cost: N/A Electricity price: 61.9 €/MWh Capacity factor: 82% (7200 h/y) Biomass cost: 5.1 €/GJ TCI PBtX (per kW_{prod}): 1871 €/kW (SNG) 1747 €/kW (M) 1962 €/kW (DME) 3288 €/kW (JF)	PBtX: 20.3 €/GJ (SNG) 22.0 €/GJ (M) 23.7 €/GJ (DME) 33.1 €/GJ (JF) BtX: 8.5 €/GJ (SNG) 11.0 €/GJ (M) 13.6 €/GJ (DME) 11.0 €/GJ (JF) e-product: *39.9 €/GJ* (SNG) *44.6 €/GJ* (M) *44.1 €/GJ* (DME)

Table 1 (continued)

Reference	Biomass input, gasification and syngas cleaning, and conditioning technology	Electrolyser technology and power to LHV efficiency	Biofuel produced	Carbon efficiency	PtX efficiency	HtX efficiency	Main data for economic analysis	Cost of product
[8]	Biomass input: 60 MW, 4.8%wt moisture. Entrained flow O_2-blown gasification, WGS, CO_2 separation and conversion in SOEC	SOEC with H_2O/CO_2 co-electrolysis η = -	SNG, M, DME, JF	BtX: *27.7%* (SNG) *35.6%* (M) *36.1%* (DME) PBtX: *86.7%* (SNG) *85.0%* (M) *66.6%* (DME)	75.3% (SNG) 76.6% (M) 48.5% (DME)[5] 63.4% (JF)	N/A	Electrolysis cost: N/A Electricity price: 61.9 €/MWh Capacity factor: 82% (7200 h/y) Biomass cost: 5.1 €/GJ TCI (per kW_{prod}): N/A	PBtX: 22.0 €/GJ (SNG) 23.7 €/GJ (M) 31.4 €/GJ (DME) 38.1 €/GJ (JF) BtX: 8.5 €/GJ (SNG) 11.0 €/GJ (M) 13.6 €/GJ (DME) 11.0 €/GJ (JF) e-product: *45.4 €/GJ* (SNG) *53.1 €/GJ* (M) *140.7 €/GJ* (DME)

[1] Economic analysis performed on plants with the same product output of 200 MW_{LHV}

[2] Breakeven electricity price to obtain the same cost of product of the baseline BtX plant

[3] Revenues from heat export are taken into account

[4] Two PtX systems are assessed with fuel output comparable to the corresponding BtX (small) and PBtX (large) plants

[5] Low efficiency, due to additional heat demand

the cost of the product (in €/GJ$_{LHV}$). It has to be noted that PtX (Eq. 1) and HtX (Eq. 2) efficiencies refer to the marginal production efficiency of the product (*prod*) between the PBtX plant and the corresponding baseline BtX without hydrogen addition. Also, the cost of the e-product has been calculated (Eq. 3), as the marginal cost for the additional fuel produced in a PBtX plant, with respect to the corresponding BtX plant.

$$\eta_{PtX} = \frac{\left(\dot{m}_{prod} \bullet LHV_{prod}\right)_{PBtX} - \left(\dot{m}_{prod} \bullet LHV_{prod}\right)_{BtX}}{P_{el,electrolysis}} \tag{1}$$

$$\eta_{HtX} = \frac{\left(\dot{m}_{prod} \bullet LHV_{prod}\right)_{PBtX} - \left(\dot{m}_{prod} \bullet LHV_{prod}\right)_{BtX}}{\dot{m}_{H_2} \bullet LHV_{H_2}} \tag{2}$$

$$C_{e-prod} = \frac{\left(C_{prod} \bullet \dot{m}_{prod}\right)_{PBtX} - \left(C_{prod} \bullet \dot{m}_{prod}\right)_{BtX}}{\dot{m}_{prod,PBtX} - \dot{m}_{prod,BtX}} \tag{3}$$

The analyzed literature assumes different plant sizes, different gasification and syngas conditioning processes, different electrolysis technologies, and economic assumptions that do not allow a direct comparison of the quantitative results. Nevertheless, the existing literature allows to make the following main observations.

- The first main benefit of PBtX plants is the much higher carbon efficiency, i.e., the better utilization of the biogenic carbon. With PBtX configurations, it is possible to achieve carbon efficiencies higher than 90% vs. 25–40% of baseline BtX plants. The relatively low carbon efficiency of the PBtX systems in [4] (42–49%) is due to the selected process configuration where only the CO in the syngas is converted and CO_2 is separated and vented.
- The HtX efficiency varies in a relatively narrow range in the reported studies (82–85% [4••, 5••, 6••, 7••]), independently from the final product. The only exception is gasoline production [4••, 5••], that is, based on a methanol-to-gasoline (MTG) process downstream methanol synthesis, that introduces energy losses. Therefore, the PtX efficiency mainly depends on the efficiency of the electrolysis system. With an efficient thermal integration with the process, high temperature solid oxide electrolyzers allow achieving a PtX efficiency approaching 80% [7••, 8], to be compared with 50–58% of systems based on low temperature electrolysis [4••, 5••, 6••].
- In PBtX plants, the increased plant productivity favorably affects the two main cost items of a bioproduct, namely, (i) the biomass cost and (ii) the capital cost of the equipment for biomass gasification and syngas cleaning and conditioning. Both these items, that are directly linked to the input of biomass feedstock in the plant, are distributed over a higher amount of final product. Such economic benefit has to be compared to the additional cost for the production of the input hydrogen.
- The cost of green hydrogen is closely linked to the following: (i) the capital cost of the electrolysis system, (ii) the capacity factor of the electrolyzer, and (iii) the average price of electricity used for hydrogen production. As clearly shown by Hannula [4••], high-capacity factors of the electrolysis system are needed to have competitive hydrogen production cost in a PBtX plant, unless (unrealistic) long periods of negative electricity price are assumed. This is the same conclusion obtained by Zhang et al. [8], who showed the significant rise in the cost of the product, when the electrolysis capacity factor reduces. So, PBtX plants cannot be economically competitive if relying only on “excess electricity” from renewable energy sources. This is the reason why all the reported economic analyses are carried out assuming high-capacity factors, ranging from 82 to 94%, and the same capacity factor for the electrolysis system and the biomass gasification and biofuel synthesis processes.
- In the reported studies, different results have been obtained for the cost of the e-product. Hannula [4••] computed a higher cost of the products produced in PBtX plants than in the corresponding BtX plant. The resulting cost of the e-product is nearly twice as high as the cost of the corresponding bio-product. Higher differences (about four times higher e-product costs) have been obtained by Zhang et al. [8] with a very different process, based on high temperature electrolysis and H_2O/CO_2 co-electrolysis. Albrecht et al. [6••] computed comparable costs for FT fuel via PBtX and BtX plants, resulting in a cost of the e-FT slightly higher or slightly lower than the bio-FT, depending on the revenues from the exported heat. From the data reported by Hillestad et al. [7••], a cost of the e-FT fuel 26% lower than the bio-FT has been computed, thanks to the optimistic investment cost of the SOEC unit and its high efficiency. From such contrasting results, it can be concluded that the economic competitiveness of a PBtX system is closely linked with the assumed cost of electrolysis and electricity (i.e., ultimately on the cost hydrogen) that will substantially depend on the evolution of the electrolysis technology and of the electricity market.
- It is interesting to compare the cost of the e-product of a PBtX plant with the cost of a PtX plant using CO_2 as carbon source. Hannula [4••] and Albrecht [6••] performed a comparison with consistent assumptions, obtaining a lower cost of the e-product in the PBtX plant compared to the PtX plant. This can be attributed not only to higher PtX efficiency [6••], but also to the lower marginal specific capital cost per unit of product of the PBtX plant compared to the capital cost of the

PtX plant. For example, from the data in [6••], it is possible to compute a marginal specific capital cost for the production of the e-FT in the PBtX plant of 3580 €/kW_{prod}, as the ratio between the marginal cost of the PBtX system compared to the BtX one (355.8 M€) and the increased product output (99.4 MW_{LHV}) for the same biomass input. This cost is about 30% lower than the estimated specific capital cost for the production of e-FT in the PtX plants.

Integration of Biomass and Power-to-X Pathways in the Energy System

Predicting the potential deployment of power-to-X pathways requires to understand the features of future energy markets, hence the evolution of electricity prices, which will be highly influenced by the penetration of intermittent renewables and on the geographic location [10]. The spread of technologies for the electrification of new sectors such as the transport sector and the production of heat for civil and industrial uses will impact on the demand side, affecting the electricity price distribution. In this respect, the techno-economic assessment of PtX and PBtX routes needs to jointly account for both these aspects.

McDonagh et al. [11] analyzed the costs of SNG from a power-to-SNG system integrated in simulated Irish electricity markets with increased penetration of renewable energy sources. Their model investigated the interplay between the simulated electricity market price and the bid price on the run hours and the average electricity price that are the most influencing factors of the produced e-SNG. Sorknæs et al. [12••] addressed the problem of re-designing the Danish electricity market under the assumption of a 100% renewable energy system, considering the mutual influence of renewable-based heating, gas, liquid fuels, and electricity markets as an interdependent energy system. The study highlighted the significant influence that the demand side could have on the electricity price duration curve. A similar conclusion was obtained by Ruhnau [13], who assessed the effect of flexible electrolysis systems on stabilizing the value of solar and wind power generation.

Similarly, the economic performance of PBtX and e-fuel production plants is highly dependent on energy market conditions. Notwithstanding the inherent complexity that would be introduced by the uncertainty in electricity penetration and prices of future electrified markets (e.g., scale of electric mobility, diffusion of electrolysers, electrification of heat supply for domestic and industrial use), the comprehensive system modeling of electricity supply and demand at electrofuel production plants is key to estimate their role and needs to be addressed further in future research.

Economic Competitivity of BtX and PBtX Processes

The scope of this section is to provide insights on how the market price of the different goods (electricity, hydrogen, and carbon-based products) and of carbon removal credits may affect the best use of biomass and on the positioning of BtX and PBtX plants among the different competing uses of biomass. To this aim, a simple economic model has been defined, computing the internal rate of return (*IRR*) and the operating revenue of (i) biomass-to-power (BtP), (ii) biomass-to-methanol (BtM), (iii) power and biomass to methanol (PBtM), and (iv) biomass to hydrogen (BtH) plants. For each of the four plant archetypes, configurations without and with CO_2 capture and storage have been considered. The economic indicators have been computed for different values of electricity, methanol, and hydrogen selling price and of the captured CO_2. It has to be noted that methanol has been selected as representative of a carbon-based product. The general qualitative conclusions obtained for methanol can be easily extended to other products.

The levelized annual cash flow CF_y (Eq. 4) is computed as the sum of the discounted annual investment, the operating costs (biomass feedstock, electricity, and O&M), and revenues (selling of methanol, hydrogen, electricity, CO_2 emission allowance). The first term is calculated from the total *CAPEX* by means of a capital recovery factor (*CRF*) defined in Eq. 5 that includes a constant discount rate (weighted annual capital cost, *WACC*) during the lifetime of the plant (*LT*). Revenues are proportional to the plant biomass input (B_{in}), the equivalent operating hours (h_{eq}), the specific yields of product ξ_i, and its unitary price p_i. Under these assumptions, the *IRR* is computed as the breakeven *WACC* value that gives a null net cash flow.

$$CF_y = B_{in} \bullet h_{eq} \bullet \sum \xi_i \bullet p_i - CAPEX \bullet CRF - OPEX \tag{4}$$

$$CRF = \sum_{1}^{LT} \frac{1}{(1 + WACC)^i} = \frac{WACC \bullet (1 + WACC)^{LT}}{(1 + WACC)^{LT} - 1} \tag{5}$$

The lifetime of all the plants is assumed equal to 20 years and the capacity factor equal to 90% (i.e., about 8000 equivalent operating hours). All the costs are scaled to a reference biomass input of 300 MW_{LHV} (LHV 15.4 MJ/kg, carbon content $38\%_{\text{w}}$, reference cost 18 €/MWh).

More specifically, the following technologies have been considered, with the assumptions summarized in *Table 2*:

i. Methanol synthesis via BtM plant based on O_2-blown gasification and via PBtM plant involving additional hydrogen from low temperature electrolysis. Costs and efficiencies are taken from [4••].

Table 2 Assumptions for the economic analysis

	Yields				CAPEX	OPEX*			
	Electricity	Methanol	Stored CO_2	Hydrogen			Carbon in products	Carbon stored	Carbon vent
	kWh_e/MWh_b	*kg/MWh_b*	*kg/MWh_b*	*kg/MWh_b*	*$€_{2017}/kW_b$*	*$€/kW_b/y$*	*$\%_w$ inlet C*	*$\%_w$ inlet C*	*$\%_w$ inlet C*
BtM	−40	108	-	-	1452	58.1	45.2	-	54.8
PBtM	−407	141	-	-	1725	69.0	59.0	-	41.0
BtM CCS	−54	108	174	-	1512	60.5	45.2	52.8	2.0
BtP	321	-	-	-	1118	29.1	-	-	100.0
BtP CCS	225	-	297	-	1891	31.6	-	90.0	10.0
BtH	27	-	-	14	2011	139.6	-	-	100.0
BtH CCS	2	-	323	14	2124	147.4	-	98.0	2.0

*In addition to reported plant OPEX, 10 €/t_{CO2} are included for CO_2 transport and storage costs in CCS cases

ii. Power production from biomass with and without CCS, considering a supercritical boiler and amine-based CO_2 capture. Costs and efficiencies are taken from [14].

iii. Hydrogen production via O_2-blown gasification and PSA separation. Costs and yields are taken from [15, 16].

iv. BtM and BtH plants with CCS considering a CO_2 compression station added to the existing CO_2 separation unit. Electricity consumption and additional costs for CO_2 compression are taken from [17]. A cost of 10 €/t_{CO2} has also been assumed for CO_2 transport and storage, which is in the lower range of the expected costs for onshore geologic CO_2 storage [18].

It is important to highlight that values used in this work have been taken from different sources and a reliable quantitative comparison would require a careful data harmonization, especially in the method for determining the *CAPEX* that has intrinsically high uncertainty and high impact on the cost of the products. Also, other features that may affect significantly the economics of a plant are not taken into account in this analysis, such as the revenues from operations in the secondary electricity market, that would increase the region of competitivity of BtP and PBtX plants, or the additional revenues from CHP configurations, that would favor BtP processes. Therefore, although based on quantitative values, this simplified analysis is intended to provide qualitative conclusions.

Figure 2 shows a map of the areas of the best plant from the point of view of *IRR* (left) and operating revenues (i.e., revenues minus *OPEX*, on the right) as function of the electricity price and of the value of the stored CO_2, for different MeOH and H_2 prices.

Looking at the IRR maps, with methanol and hydrogen prices similar to the current ones (a), with intermediate electricity prices and low CO_2 value, the BtM system results the most competitive option, although with modest economic competitiveness, as the *IRR* is relatively low. Power production is favored at high electricity prices. BtM with CCS is the most profitable option if the CO_2 value rises above 20 €/t_{CO2}. PBtM system is the most competitive process for low electricity prices (below 25 €/MWh), unless the value of CO_2 rises above 30–50 €/t_{CO2}, making CO_2 sequestration more profitable than CO_2 conversion into e-methanol.

Increasing the value of methanol to 600 €/t (c) leads to improved economics for all the methanol production plants. The competitiveness of PBtM process expands towards the BtM region. BtP process remains competitive only for very high electricity prices (> 150 €/MWh). BtH processes become competitive with high hydrogen price (e) and is favored by high value of CO_2 when CCS is included.

Looking at the operating revenues maps (Fig. 2, on the right), some differences emerge in the areas of convenience compared to the *IRR* maps. The area of convenience of the PBtM plant expands in the first two scenarios (b–d) compared to the *IRR* indicator (a–c). This means that it is economically competitive to run a PBtM plant for higher electricity prices (e.g., approaching 50 €/MWh when MeOH price is 600 €/t), but lower average electricity prices are needed to make PBtM the most profitable option from the *IRR* perspective and generate sufficient revenues to pay back the higher capital investment compared to the BtM cases. In the third scenario (f), the BtH area enlarges significantly when looking at the operating revenues. Similarly to the previous comment, this reflects the behavior of a case with higher operating revenues but higher capital costs than the other technologies at the boundaries.

The operating revenue charts also show that flexible plants may take advantage from the variable market prices over time. For example, depending on the electricity price (that varies on daily and seasonal time scales), on the hydrogen price (that in the future may fluctuate on a seasonal basis, depending on the availability of green hydrogen), on the CO_2 value (with expected variations on multi-year time

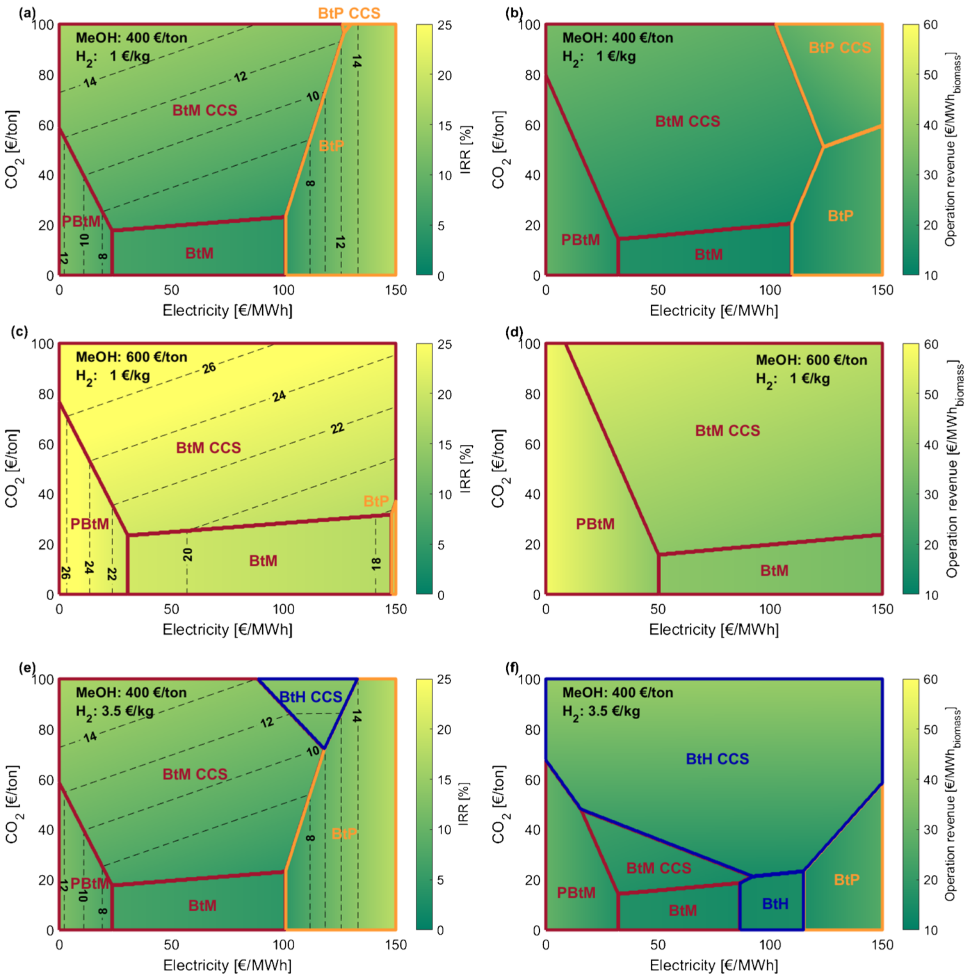

Fig. 2 IRR (**a**, **c**, **e**) and operation revenue (**b**, **d**, **f**) maps for BtM, PBtM, BtP, and BtH plants with and without CCS. Lines identify the boundary of the regions of the most profitable options for different values of electricity, CO_2, methanol, and hydrogen.

scales), and the methanol price variability (dependent on the evolution of the demand), a flexible plant could switch its operating mode from BtM (without or with CCS), PBtM, and BtH.

Conclusions and Research Gaps

The evolution of the power, CO_2, H_2, and carbon-based product markets will increase the competition between different uses of biomass. In a carbon-constrained world with high penetration of intermittent renewables, key drivers for the optimal exploitation of biomass will be the achievement of high efficiency in biogenic carbon utilization, either as a high-value product or as sequestered CO_2, and the efficient utilization of its dispatchable renewable energy content.

Recent literature on power and biomass-to-X processes have assessed the techno-economic performance of such systems, highlighting the importance of low-cost hydrogen supply and the economic competitivity with respect to power-to-X systems based on the conversion of CO_2 from other sources. From a simplified economic analysis, this paper showed that additional value may be obtained from operating biomass-to-X plants flexibly, e.g., modifying the electric power consumption, the destination of the biogenic carbon or the type of bio-product over time, following the market and regulatory conditions.

On this regard, the following main research gaps may be highlighted:

- none of the assessed recent papers on PBtX systems investigates the design of the process units of plants conceived to operate flexibly. The economic performance of the plants are computed by fixing the electricity price and assuming that the electrolysis system operates continuously, at the same capacity factor of the biomass conversion process. The effect on the capital and operating costs of plants conceived to operate flexibly is currently unexplored in the open literature.
- The expected capacity factor of the electrolysis system of a PBtX plant is closely linked with the expected electricity price curve, which will depend on factors such as the geographic location, the type of renewable energy sources, their penetration in the regional grid, and the

willingness to pay of other potential users of electricity connected to the grid. Therefore, to understand the potential of PBtX plants and the value of their flexibility for the energy system, the integrated modeling of plants connected to electric grids of the future should be pursued.

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Declarations

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest The authors declare no competing interests.

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• Of importance
•• Of major importance

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