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What is the level of incentivisation required for biomethane upgrading technologies with carbon capture and reuse?

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Abstract

This paper documents a techno-economic assessment of biomethane feedstocks from urban, rural, and coastal settings. Additionally, the effect of three upgrading technologies was investigated, ranging from commercialised systems (water scrubbing) to more advanced systems: power to gas systems employing hydrogen to capture CO_2; and micro-algae cultivation utilising CO_2 in biogas. In total, nine scenarios were investigated based on a combination of the three feedstock groups and the three upgrading technologies. The levelized cost of energy and the incentive required to allow financial sustainability were assessed. The assessment showed that that water scrubbing was the cheapest upgrading method. The optimum scenario was the combination of urban based feedstock (food waste) with water scrubbing upgrading costing 87€/MWh, equivalent to 87c/L diesel equivalent. The incentive required was 0.13 €/m^3 (or per L of diesel equivalent), however if power to gas was used to upgrade an incentive of 0.40 €/m^3 was required. This was expected as food waste attracts a gate fee. Rural-based plants (using slurries and grasses) are expected to provide the majority of the resource however, for this to become a reality incentive in the range 0.86 to 1.03 €/m^3 are required.

Keywords: biogas; biogas upgrading; biomethane; carbon capture and reuse; power to gas; techno-economic analysis.

1 Introduction

When biogas is upgraded to renewable methane, through removal of CO_2 and injected to the gas grid, it has a range of applications including provision of renewable heat, electricity and/or transportation fuel. In 2015, there were 459 biogas-upgrading plants in operation in the EU producing 1,230 M Nm^3 of biomethane [1] . According to the Sustainable Energy Authority of Ireland (SEAI) Ireland has a biogas potential of 0.95 Mtoe, but less than 2% of this is currently utilized [2] with no gas to grid system in place as of yet in Ireland.

The sustainability criteria in the recast Renewable Energy Directive (recast RED) includes for a proposed 75% greenhouse gas (GHG) savings as compared to the fossil fuel comparator (FFC) for renewable heat by 2026. For mono-digestion of crops this level of sustainability is highly unlikely [3]. This can cause developers to consider whether it is prudent to invest in technologies today that may be deemed unsustainable in 8 years' time.

Increased sustainability is expected to be associated with concepts such as BioEnergy with Carbon Capture and Storage (BECCS) [4] and also with reuse of captured carbon. Power to gas (P2G) systems may be used to upgrade biogas to biomethane, capturing CO_2 from the biogas and reacting with hydrogen from electrolysis to produce renewable methane ($4H_2 + CO_2 = CH_4 + 2H_2O$) as described by Ahern et al [5]. Another method of carbon capture is to combine micro-algae cultivation with removal of CO_2 from biogas as described by Xia et al. [6] . The literature is sparse in assessing the financial sustainability of such systems and assessing the cost to capture and reuse this CO2.

The assessment of the financial feasibility of biogas systems may be simplified via process simulators, which allow techno-economic analysis (TEA) [7]. TEA considers process level information such as yield, sizing, and productivity. Previous techno-economic assessments on AD includes retrofitting and expansion of a biogas facility [8], exploring digestion of forestry feedstocks with innovative pretreatments [9-11], and upgrading technologies [12, 13]. Most AD plants employ conventional upgrading technologies (water scrubbing, absorption or adsorption) that have a high technology readiness level (TRL) to purify biomethane [13]. However, conventional upgrading processes do not readily capture pure streams of CO_2 after upgrading for further use as a fuel. Capture and reuse of released CO_2 in cascading bioenergy systems can facilitate further reduction in greenhouse gas emissions [14]. New technologies such as Power to Gas (P2G) and microalgae-based upgrading offer CO_2 capture and reuse combined with upgrading [14, 15]. P2G would be at a lower TRL than conventional upgrading, while microalgae upgrading would be at a lower TRL again[16].

The gap in the state of the art is the lack of detailed financial assessment of carbon capture and reuse from a biogas system and the extra cost as compared to conventional upgrading. No previous study has evaluated the incentives required to operate a biogas plant using a range of feedstocks (such as from urban, rural and coastal regions) that employ different upgrading systems including for carbon capture and reuse.

The innovation in this study is that BECCS is seen as critical for the below 1.5 degree temperature rise scenario. CO_2 from biogas upgrading is one of the most concentrated sources of CO_2 thus minimising the cost of Power to Gas systems [5]. This paper assessed, through a techno-economic analysis, the incentives required for conventional water scrubbing and the increased incentive required for scenarios that capture and allow reuse of carbon such as microalgae upgrading and power to gas systems. The innovation was shown through satisfying the following objectives:

1. Develop simulations of renewable methane from nine models using feedstocks from urban, rural, and coastal wastes using three upgrading techniques (water scrubbing, microalgae upgrading and power to gas).
2. Calculate the levelized costs of energy (LCOE) over the plant lifetime of the nine scenarios.
3. Assess the level of incentives required for the three upgrading mechanisms.
4. Calculate the extra incentive to facilitate carbon capture and reuse.

2 Methodology

Substrates were chosen based on urban, rural, and coastal models while upgrading methods were chosen based on the maturity of technology; water scrubbing, microalgae upgrading and P2G. The combination of feedstock and upgrading methods resulted in the simulation of nine scenarios (Figure 1). Food wastes dominated the urban scenario, while for rural regions grass silage and slurry were the model feedstocks. The coastal model utilised slurry, grass silage, food wastes and seaweed. The choice of feedstock and upgrading method was used to label each scenario; urban feedstock was labelled as "U," rural as "R" and coastal as "C". Labelling upgrading methods used the following acronyms: "WS" for water scrubbing; "P2G" for power to gas systems; and "MA" for microalgae upgrading. A scenario employing coastal feedstock and power to gas upgrading therefore has an acronym of "CP2G".

2.1 Feedstock characteristics

2.1.1 Urban scenarios

Urban organic wastes, predominantly food wastes (FW) are modelled with a per-capita food waste (FW) generation of 180 kg/per person/ per year, which is the typical Irish production [17]. The design of the plant ensured feedstock availability within a 40 km radius; transporting longer distances would not be economically viable [8]. The population of Dublin (the capital city of Ireland) facilitates an annual processing capacity of 100,000 t/yr. Hence, the urban scenario had a processing capacity of 274 t FW/day. Table 1 shows the characteristics of the feedstocks including total solids (TS), volatile solids (VS) and biomethane potential (BMP). The EU Landfill Directive in essence prevents landfill of organic wastes; this disincentive is facilitated in Ireland by the introduction of tipping fees of the order of €75/t. In this study, it was assumed that FW would be treated in the AD facility at a gate fee of €50/tonne (which is cheaper than landfill). This charge is a significant source of revenue for treating wastes [18] and has been a driver for the first biogas facilities in Ireland. It is assumed that the FW is source segregated and collected using a separate bin for organics. The waste collection trucks collect the FW from households once a week and transfer it to the AD processing facility.

2.1.2 Rural scenarios

Rural areas contain agricultural residues such as grass silage (GS) and cattle slurry (CS). In Ireland, grass silage production was of the order of 26 Million tonnes in 2009. There is significant potential to allow feed and energy supply [22]; estimates of a biomethane potential of 138 PJ per annum are suggested in the literature [19, 20]. Ireland in 2016 has a population of about 6.6 M cattle, including for 1.3M dairy cows [23]; the slurry produced has a biomethane potential of 13.7 PJ [23]. Dairy cows at two-years-old produce approximately 50kg slurry/day; if we assume a farm size of 100 cows 5 t/day of slurry is produced [19].

The carbon to nitrogen (C:N) ratio of grass silage is high (of the order of 30:1) [21] while that of slurry is low; co-digestion enhances the balance in the system as well as boosting the methane yield [25]. In a study by Wall et al., the optimum grass silage to the slurry ratio in long term continuous anaerobic digestion in terms of methane yield and sustainability was 80:20 by volatile solids ratio [22]. If we model a co-op of 35 Irish cattle farms each with 100 cattle (or 3500 cattle in total) then the slurry production is 65,000 t/yr of slurry; then to maintain a VS ratio of 20:80, the amount of grass silage used should be 75,000 t/yr. A 20:80 slurry: silage VS ratio equates to a 46:54 slurry: silage wet weight ratio. Moreover, as grass silage (ca. 29% TS) has a high dry solids content, while slurry has a high-water content (90 – 94%), combining the two substrates leads to a mixable pumpable digestate. The cost of GS was modelled at €27/t, while slurry was costed at the cost of transportation alone. Transportation of slurry was assumed at a cost of €4/t. Grass silage and slurry are abundant in the south-west of Ireland where this facility is assumed to be built. The BMP of the combination of GS and CS used in the techno-economic assessments was 366 LCH_4/kgVS at a loading rate of 3.5 kgVS/m^3/day with a retention time of 25 days (Table 1) as per Wall et al., [25].

2.1.3 Coastal scenarios

Coastal areas produce wastes from diverse origins including food wastes, grass silage, slurry, and seaweed. Ireland harvests about 30,000 t/year seaweed, which corresponds to 2.5% of the global seaweed harvest [23]. The biomethane potential varies based on the species, and in this study, *L. digitata* was modelled with data from Allen et al. [24]. The coastal biogas production process considered 5,000 t/yr seaweed, 50,000 t/yr silage, 45,000 t/yr slurry and 2,000 t/yr FW (Table 1). It is assummed that cast seaweed of nuisance value is collected from beaches to improve amenity and as such the cost is minimal; a transportation cost of €4/t is modelled similar to slurry. In Timoleague in West Cork approximately 10,000 t of dry solids seaweed is cast on the shore each year. In Solrod, Denmark, beach cast seaweed is digested with by-products of a seaweed processing industry [25].

2.2 Model Development

This study used Intelligen SuperPro Designer (V 10.0) to develop the process models. The outputs of the process models are attached as supplementary files to facilitate transparency and reproduction of work.

2.2.1 Biogas production (Upstream Processing)

The screening of FW in urban scenarios helps in removing metals, plastics or any foreign objects in the first step. One percent of waste entering the facility is assumed to be screened before further processing takes place. This low level of contaminants requires excellent quality control in collection of food waste. An assumption here is that small amounts of food waste in small containers are collected on a frequent basis and that any contaminated bins are rejected leading to good practice over time. Screening was also used in coastal scenarios for FW. Except for slurry, all the wastes were stored in a silo, as a temporary storage upon arrival to the treatment facility. The solid wastes were screw conveyed to the shredder with an electricity consumption of 0.02 kW/(kg/h). The carbon steel shredder reduces the incoming feedstocks with a power consumption of 0.09

kW/(kg/h) [26]. Figure (i) (Appendix A) shows the complete process flow from SuperPro Designer for the UWS scenario.

The digestate after AD is rich in microbial consortia and water; this is recycled back to the process together with the incoming feedstock through a centrifugal pump. Rural and coastal scenarios handling cattle slurry incorporated mixing after shredding the feedstock prior to pumping and pasteurization. To facilitate pumping, the processed feedstock had a solids concentration of between 12-15% [8, 9, 27]. The pumped materials were sent to a pasteurization tank operated at 70°C with a 1 hour retention time to kill the pathogens present [28, 29]. The excess heat post-pasteurization is heat exchanged with the incoming feed to reduce the heating load. The pasteurized feed was stored in a storage tank with a retention time of 10 hours before it was transferred to the main digester. The pasteurized feed was stored in two parallel storage tanks with a volume between 90 and 130 m^3 depending on the scenarios.

Table 1 depicts the operating conditions including loading rate and retention times for different feedstocks considered. The digesters operated at mesophilic conditions (37°C) and consumed 0.01 kW/m^3 for agitation purposes. The TS in the digestate post AD varied between 4 and 6% depending on the feedstock. Two digesters arranged in series were in operation for Urban and Rural scenarios whereas for coastal feedstock one was sufficient. The experimental data from the literature provided the methane yield for different feedstocks used in this study (Table 1). After AD, the gaseous stream was upgraded to biomethane. Farmers use the digestate after concentration free of cost. The model uses a decanter to concentrate the digestate to TS content of between 7 and 10%. The remaining water is recycled to the process. The concentrated digestate is stored in storage tanks for 90 days before distribution to farms. Conditioning the biogas is necessary for upgrading; a moisture-trap removes excess moisture. The moisture free biogas is upgraded either by water scrubbing, power to gas or microalgae.

2.2.2 Water Scrubbing

Water scrubbing is widely used as an upgrading method for biogas with more than 145 units installed to date [30]. It is potentially the cheapest biogas upgrading method available [31]. The WS scenarios did not capture carbon dioxide after biogas upgrading. The other two scenarios require carbon capture.

In this WS model, water is pumped to the top of the absorption column at 7 bar pressure, while the biogas is compressed to 4 bar before it is fed to the bottom of the column (Figure (i) Appendix A) [32]. The solubility of the gases in the absorption column was designed based on Cozma, Wukovits, Mămăligă, Friedl and Gavrilescu [33]. The absorption column was designed using carbon dioxide as a design component with a gas and liquid phase diffusivity of 0.016 and 0.087 m^2/s [34]. The absorption column had a length of between 15 and 25 m with a diameter of 1.05 m. The column was packed with plastic pall rings that had a surface area of 128 m^2/m^3 with a critical surface tension of 0.072 N/m [35]. A methane purity of between 96-98% is achievable from the absorption column; this was compressed to a pressure of 8 bar to maintain the gas pressure standards injecting into the grid [36]. The liquid stream from the absorption column is rich in dissolved carbon dioxide and includes for dissolved methane; this is passed through a flash vessel to recover the methane.

Regenerating the water and reusing it in the absorption column reduces the requirement for fresh water consumption and hence the environmental load. Similarly, a heat exchanger cooled the water (with absorbed carbon dioxide from the flash vessel) to 20°C; from here it is sent to a stripper. In the stripper, the injected air when contacted with the cooled water strips the carbon dioxide. The operating conditions of the stripper column were similar to the absorption column, whereas the gas and liquid diffusivity were altered to 0.001 m^2/s [34]. Emitting the stripped carbon dioxide from the water into the atmosphere, helps in recycling water to the process. To avoid saturation of liquid, five percent of regenerated water was replaced with fresh water.

2.2.3 Microalgae Upgrading

The microalgae upgrading process involves a carbonate-bicarbonate system where the carbonate reacts with the carbon dioxide resulting in bicarbonate formation [37, 38]. Microalgae uses this bicarbonate for growth and converts the bicarbonate back to carbonate, which is then recycled back to the process [16, 39] (Figure (ii) Appendix A). The raw biogas is compressed initially to four bar and enters the absorption column that works similar to a WS with a modification. Instead of water, this column uses carbonate solution for trapping carbon dioxide (Equation 1). The bicarbonate-rich solution then enters the algal raceway-pond for microalgae cultivation that eventually releases carbonate for the next cycle. Design considerations include the length-to-width ratio of the pond (10:1) and a depth of not greater than 0.3m [40]. Three reactions occur in an algal pond including: release of carbon dioxide (Equation 2); bicarbonate conversion to carbonate (Equation 3); and finally utilizing carbon dioxide to produce algae (Equation 4) [38]. The algal cultivation had a retention time of 15 days, with the following dimensions for the urban scenario (UMA): 416 m (L) × 41 m (W) × 0.3 m (H). Cultivating microalgae for an urban scenario needs eight hectares of land space. The concentration of the algae produced from the raceway pond was limited to 4.8 g/L with a conversion efficiency of between 60 and 65% [41]. Clarifying and centrifuging the low concentrated algal biomass results in selling the microalgae as a by-product, while venting oxygen. Clarifying and centrifuging has an additional advantage in enhancing recirculation of the carbonate-rich solution back to the process. The carbonate losses ranged between 10% and 15%; fresh carbonate replaces the loss at the start of the process (Figure (ii), Appendix A). Compared with P2G upgrading that produces additional methane, MA upgrading interchanges bicarbonate to carbonate to produce microalgae as a by-product. Microalgae have commercial value as a precursor for biogas or biodiesel or other edible applications [42].

$$CO_2 + Na_2CO_3 + H_2O \rightarrow 2\ NaHCO_3 \qquad \text{Equation 1}$$

$$NaHCO_3 \rightarrow CO_2 + NaOH \qquad \text{Equation 2}$$

$$NaHCO_3 + NaOH \rightarrow Na_2CO_3 + H_2O \qquad \text{Equation 3}$$

$$CO_2 + H_2O \rightarrow Algae + O_2 \qquad \text{Equation 4}$$

2.2.4 Power to gas

Power to gas (P2G) technology utilizes electricity (ideally surplus intermittent renewable electricity such as from wind turbines) to produce hydrogen by electrolysis. This hydrogen may be reacted with carbon dioxide from biogas to produce methane (Figure (iii) Appendix A) [43]. The carbon dioxide from the biogas needs to be free of hydrogen sulphide and other impurities before catalytic methanation can take place. A desulfurizer is employed to remove hydrogen sulphide in a two-step process [44]. The first step involves the conversion of Iron (III) oxide monohydrate to Iron (III) sulphide monohydrate (Equation 5). Later, the

Iron (III) sulphide monohydrate when oxidized regenerates Iron (III) oxide hydrate and the cycle continues [45] (Equation 6).

$$Fe_2O_3.H_2O + 3H_2S \rightarrow Fe_2S_3.H_2O + 3H_2O \qquad \text{Equation 5}$$

$$2Fe_2S_3.H_2O + 3O_2 \rightarrow 2Fe_2O_3.H_2O + 6S \qquad \text{Equation 6}$$

The electrolyser uses electricity to split hydrogen from water [46] (Equation 7). The size of the electrolyser depends on the amount of the CO_2 in the biogas, an important design parameter. The electrolyser operates at 250°C, 10 bar pressure and is modelled with a conversion efficiency of 72% [15, 46]. Multiple units of electrolysers are considered when the size of the electrolyser exceeds 10MW. The cost of the electrolyser was based on previous literature [43].

$$2H_2O \rightarrow 2H_2 + O_2 \qquad \text{Equation 7}$$

Upon hydrogen production, both the reactants (biogas and hydrogen) enter the catalytic methanation unit operating at 200°C [47] where the carbon dioxide reacts with hydrogen to produce methane and water (Equation 8). The efficiency of the catalytic methanation was modelled at 78%. This results in an overall efficiency combining electrolyser and catalytic methanation of 56% [15, 43, 47].

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \text{Equation 8}$$

2.3 Economic analysis and assumptions

The economic assumptions behind play a vital role in the results obtained from SuperPro Designer. Table 2 outlines the assumptions used in this study including the utilities cost and selling price of products such as methane and algae. The scenarios considered 20 years as the lifetime of the plant, with a construction period of 18 months and start-up period of 6 months. Table 1 shows the capacity of different feedstocks in each scenario considered with their associated costs. Food waste yielded gate fees of € 50/t. SuperPro Designer calculated the sizing and costing of different equipment while the digester costs were from taken from Krieg & Fischer [48]. The equipment depreciation calculation used a straight-line method that had a depreciation period of 10 years and a salvage value of 5% of direct fixed capital (DFC). Corporation tax in Ireland is 12.5%. The start-up costs account for 5% of DFC while the working capital depicts one-month operational expenses. This project assumed equity-based financing on different sections including 9% interest on DFC, 12% for working capital, research, and development. DFC had a loan period of 10 years while the rest of the equipment had 6 years. Purchasing electricity was one of the key assumptions and the main economical variable in P2G systems. It is assumed that the developer bids for electricity in the open market as a wholesaler. Electricity is bid at 50€/MWh yielding an average price of 35€/MWh [5]. The biomethane produced was sold at a base price of 0.20 €/m^3 [49], which is the typical price of natural gas in Ireland.

2.4 Sensitivity analysis

The sensitivity analysis illustrates the impact of fluctuations on important parameters in the system on the output. The analysis assessed variables in scenarios that could allow feasibility with an incentive of 0.5 €/m^3 methane to meet the levelized cost of energy (LCOE). This equated to a total cost of 0.7 €/m^3 or €0.70/ L diesel equivalent. Any scenario that required an incentive of greater than 0.5 €/m^3 methane was not considered for the sensitivity analysis (Figure 2). A number of parameters were assessed such as: capacity;

selling price of methane; purchase cost of electricity in the electrolyser; purchasing cost of feedstock; gate fee for the food waste. The fluctuation in capacity highlights the impact of economies of scale. Variations of between ±10 and ±20 percentage were assessed for effect on economics of the systems.

2.5 Uncertainty analysis (Monte Carlo Simulation)

Uncertainty analysis estimates the ambiguity in a calculation methodology. The Monte Carlo simulation helps in finding this ambiguity based on the data from the sensitivity analysis carried out. Figure 2 shows the methodology on the choice of scenarios considered for the sensitivity and uncertainty analysis. The sensitivity analysis had a range of ±10 and ±20 percentage fluctuation yielding a broad range of incentive values. This range of incentives was used as the input for the Monte Carlo simulation. About 1000 random incentive values were generated based on the average incentive and standard deviation from the sensitivity analysis. The Monte Carlo simulation resulted in a global mean incentive, standard deviation and the probability of achieving an incentive greater than 0.2 €/m^3 from the sensitivity analysis.

3 Results and Discussions

3.1 Technical analysis

Under nine scenarios (3 feedstocks × 3 upgrading technologies), the techno-economic performance of biogas upgrading with or without carbon capture and reuse was evaluated. Figure 3 shows the overall mass balance of the nine scenarios assessed using SuperPro

Designer®. The biogas flowrate after the AD process for the urban, rural and coastal feedstocks was around 2300, 1700 and 1300 m^3 STP/h respectively. The composition of methane in the biogas varied between 55 and 61% depending on the feedstock. Depending on the upgrading method employed, the final biomethane production varied. For example, P2G utilises the CO_2 in biogas, to produce methane which resulted in significantly more methane (practically double) unlike WS, which released the CO_2.

Urban scenarios needed a larger digester (20,200 m^3), in comparison with rural or coastal scenarios. Table 3 shows the sizing and costing of different equipment used in various scenarios. The biogas flowrate from each feedstock determined the sizing of the upgrading equipment. For example, UWS had a 22-m^3 absorption/stripper column while the RWS and CWS had 17 and 13 m^3 columns respectively. Similarly, the size of the electrolyser depends on the amount of hydrogen needed to react with CO_2 (Equation 8) that in turn depends on the biogas flow rate. The size of the electrolyser varied between 10 and 18 MW depending on the substrate [15, 46]. Microalgae upgrading requires a land space between 4 and 7 hectares of land for cultivation.

Table 4 shows the different utilities such as electricity, steam and chilled water consumed in different scenarios. WS consumed less utilities when compared with P2G or MA. There is more certainty and optimisation associated with the high TRL of WS. The electrolyser needed between 80,000 and 142,000 MWh electricity per annum to produce hydrogen to react with CO_2 to produce methane. Urban scenarios consumed more utilities than rural or coastal scenarios. Microalgae energy consumption is attributed to the aeration in the raceway pond at 8 watt/m^3 (0.05 V/V/min).

The primary concern in this paper is the effect of the upgrading technology on the biomethane production. As such Figure 4 shows the energy consumption rate and energy consumption for different scenarios based on a per t or a per m3 basis. UP2G consumed 0.33 MWh of electricity / t, a consumption rate of 17% of the energy produced (parasitic energy demand). On the other hand, WS as an upgrading method had the lowest parasitic energy demand of between 12% and 14% (Figure 4a). WS has a parasitic energy demand of 0.13-0.15 kWh electricity / m^3 renewable methane, while MA had 0.25 and 0.28 kWh / m^3 and P2G 1.02 and 1.05 kWh / m^3 (Figure 4b). It is worth noting that the energy consumption to produce renewable methane varied mainly due to the upgrading method employed. For instance, P2G utilised CO_2 that resulted in more methane, which decreased the energy consumption per unit of renewable methane production. Compared with UWS, UP2G produced 70% more methane through conversion of CO_2.

3.2 Economic analysis

The economic analysis includes evaluating the capital costs, the operational costs, and other essential parameters that measure profitability. Table 3 shows the sizing and costing of all unit operations considered in various scenarios. Dividing the scenarios into biogas production and upgrading results in identifying the costs associated with each section. The equipment costs were highest for the urban feedstock (36 €/t/yr) followed by rural (20 €/t/yr) and coastal scenarios (18 €/t/yr). The higher costs for urban scenarios could be mainly attributed to the higher solids handled in comparison with rural or coastal feedstocks. Total equipment costs for each scenario was calculated by summing the costs of biogas production and upgrading type (Table 3).

The equipment costs in the upgrading section were highest for P2G in the range of 0.124 to 0.152 €/m^3/yr followed by MA (0.08 – 0.10 €/m^3/yr) and WS (0.04 – 0.056 €/m^3/yr). The electrolyser cost between 18 and 21% of the total equipment costs (Table 3: A+B+C) in P2G upgrading. The size of the electrolyser varied between 10 and 18 MW depending on the feedstock and biogas flow rate [15, 46]. WS as an upgrading method had lower equipment costs, as it is a mature technology with more than 100 upgrading units installed by 2015 [30].

CAPEX accounts for the total investment required to build a biogas plant including for the different biogas upgrading methods. The choices for upgrading methods considered with or without carbon capture and reuse. The CAPEX for biogas production was highest for urban scenario (278 €/t.yr), followed by rural (160 €/t.yr) and coastal (141 €/t.yr) feedstocks. Urban scenarios treating 100,000 t/yr had a CAPEX between 32 and 50 M€ depending on the upgrading method used. P2G as an upgrading method for the Urban scenario treating 100,000 t/yr needed a CAPEX of 22 M€ (Figure 5a). The CAPEX differentiation between water scrubbing and power to gas was 177€/t/a (Urban). For rural scenarios the differentiation was 111 €/t/a, and for coastal scenarios €82/t/a (Figure 5a). P2G was the most expensive upgrading method requiring between 44 and 46% of the CAPEX followed by MA and WS. It is worth mentioning that P2G and MA have a significant lower TRL that leads to less defined but significantly higher costs; these costs may reduce with the improvements in the technology [15, 46].

The OPEX included labour, raw materials, utilities and facility dependent services for running a plant. The OPEX for WS varied between 64-87 €/t depending on the feedstocks, while for MA it was 72-110 €/t and for P2G it was 108-166 €/t (Figure 5b). The OPEX for P2G was higher due to the higher electricity consumption.

Apart from selling biomethane, urban scenarios yield a revenue of 50€/t from the gate fee that helps in recovering the OPEX, while the revenues did not match the OPEX in other feedstocks. For the UWS scenario, the OPEX was 87 €/t, while the revenues were 73 €/t (Figure 5c) and as such an incentive of 14€/t is required to recover LCOE. Unlike urban scenarios, the rural and coastal feedstocks generated most of their income by selling upgraded biomethane and as such need higher incentives.

The production costs showed an increasing trend with the type of feedstock and upgrading method used (Figure 6a). the urban scenario had the lowest production cost (0.73 – 0.94 €/m^3 renewable methane), while coastal scenarios had the highest production costs (1.04 – 1.37 €/m^3). WS was the cheapest upgrading method requiring between 0.12 and 0.21 €/m^3 to upgrade the biogas. The fluctuation in the production costs of WS was mainly due to the fluctuation in the biogas flow rate. As the biogas flow rate increased, the cost to upgrade decreased due to the economies of scale. UWS produced 2300 m^3 biogas STP/h followed by RWS with 1700 m^3 STP/h and coastal feedstock had a biogas flow rate of 1300 m^3 STP/h. UWS had an upgrading cost of 0.12 €/m^3 while CWS cost 0.21 €/m^3.

The MA upgrading method cost between 0.24 and 0.37 €/m^3. A general trend of decreasing biogas flowrate in different feedstocks (urban to rural to coastal) led to increased production costs. In addition, the varying biomethane yield and capacity altered the biogas flowrate that in turn affected the production cost.

For UWS scenario, the production cost was 0.73 €/m^3 and by selling the biomethane and availing of revenues from tipping fees a unit revenue of 0.62 €/m^3 was achieved. Thus, an incentive of 0.13 €/m^3 is required to meet the overall costs at zero profit (Figure 6b). An additional 2 c/m^3 was added to allow a marginal income beyond the CAPEX; this was applied in all scenarios. The incentive requirement varied based on the feedstock and upgrading method employed. For urban feedstocks, the incentives required were between 0.13 and 0.40 €/m^3 biomethane while rural feedstocks need an incentive between 0.85 and 1.03 €/m^3. A cut-off ranges of 0.5 €/m^3 was considered for applying sensitivity analysis. Hence, rural and coastal feedstocks were not considered for sensitivity and Monte Carlo simulation (Figure 6).

3.3 Sensitivity analysis on urban scenario

The sensitivity analysis included the most important factors that affect overall profitability. The factors assessed includes capacity, electricity cost, biomethane price, and gate fee. From the base case, ±10% and ±20% was considered as fluctuations. For water scrubbing and microalgae upgrading, the electricity cost had negligible effect on the incentives required (Figure 7a and 7b). Whereas for P2G upgrading, electricity cost was the second most important factor after capacity variations. When the electricity cost reduces by 20% in P2G, the incentives required decreased to 0.33€/m^3, from 0.40€/m^3 in the base case (Figure 7c). For UWS, increasing the gate fee by 20% reduced the incentives required from 0.13 €/m^3 (base case) to 0.05 €/m^3. Biomethane price had a lower effect on the sensitivity analysis in comparison with gate fee. The gate fee generated higher income (0.25 and 0.43 €/m^3) in comparison with the revenues from biomethane (0.2 €/m^3) for urban feedstocks in the base case (Figure 6b). This shows that gate fee is a more important factor than biomethane price. Of the different factors assessed, decreasing the capacities had the most negative impact on the incentive required. This suggests that bigger plants are needed to yield profits in Ireland.

3.4 Uncertainty analysis on urban scenario

A Monte Carlo simulation was performed to assess the uncertainties. The data from the sensitivity analysis was used to run the Monte Carlo simulation. The chance of incentive requirement greater than 0.2 €/m^3 was used as the criteria in uncertainty analysis. Figure 8 shows the results from a Monte Carlo simulation with 1000 iterations. The global average incentive required for UWS was 0.13±0.04 €/m^3, which had between 4% and 6% chance of incentive requirement greater than 0.2 €/m^3. The other two upgrading methods (UMA and UP2G) would need 100% higher incentives than 0.2 €/m^3. The global average incentive required for microalgae and power-to-gas systems was 0.33±0.04 €/m^3, and 0.40±0.04 €/m^3 respectively. Compared with water scrubbing, microalgae and P2G offers carbon capture, which necessitates higher incentives. The probability of incentive requirement greater than 0.5 €/m^3 was 0% for water scrubbing and microalgae upgrading; P2G had a 1% chance.

3.5 Comparison of data with literature

The Levelized cost of energy (LCOE) corresponds to the net cost of the energy incurred by the plant over its lifetime divided by the net energy produced over its lifetime (Equation 9). LCOE helps in comparing costs of different technologies through use of a uniform unit that facilitates comparison. Figure 9 shows the LCOE of different biochemical technologies and results from this study. The results from this study have an LCOE between 0.02 and 0.04 €/MJ of biomethane produced. It is worth mentioning that algal biodiesel and Fischer-Tropsch diesel had an LCOE of the order of 0.06 €/MJ and biochemical ethanol production varied between 0.01 and 0.07 €/MJ depending on the feedstock and processing method

[50]. The results for LCOE reported from this study, and other biochemical technologies from the literature were comparable. Such data allows assessment of a range of incentives required to allow countries to decarbonise at minimal cost to the taxpayer.

$$LCOE = \frac{[CAPEX\ (€)] + [OPEX\left(\frac{€}{yr}\right) \times 20\ (yrs)]}{\left[Biomethane\ produced\left(\frac{m^3}{yr}\right) \times 20\ (yrs)\right]} \qquad \text{Equation 1}$$

WS upgrading is widely used across the AD facilities, as it is cost and energy efficient. The investment costs, energy and production cost of different studies reported in the literature were compared and analysed with the data from this study. The investment costs of biogas upgrading were measured based on the raw biogas flow rate (Nm^3/h); this decreased exponentially with the increase in flow rate for lower flows [51-53]. Bauer reported the cost curve showing the specific investments costs at different biogas flow rates [13, 54]. The coastal scenarios had the lowest biogas flow rate at about 1300 Nm^3/h while the rural and urban scenarios matched with the literature (Figure 10 a)[55]. The reason for the higher costs could be due to the lower biogas flow rates, the amount of CO_2 in the raw biogas and operating conditions.

The energy consumption in this study for WS upgrading ranged between 0.20 and 0.25 kWh/ Nm^3 : this fits the literature curve [13, 27, 54, 56] (Figure 10b). There were certain outliers at lower biogas flow rates that could need to be investigated on a case-to-case basis [57, 58]. Bauer et. al [13] reported energy consumption between 0.20 and 0.30 kWh/ Nm^3 depending on the flow rate where lower flow rates consumed higher energy. The production costs in this study varied between 0.12 and 0.21 €/m^3 biomethane produced. The production costs reported in the literature varied between 0.09 and 0.30 €/m^3 biomethane [59, 60].

4 Conclusions

A techno-economic assessment was carried out for feedstocks associated with different regions. In the Urban (U) scenarios the model feedstock was source segregated food waste, in the Rural (R) scenarios slurry and grass silage, whilst for Coastal (C) scenarios source segregated food waste, grass silage and seaweed was the modelled feedstock. Three upgrading technologies were employed which were at different technology readiness levels. Commercialised water scrubbing (WS), power to gas systems (PG), at demonstration level, and micro-algae (MA) upgrading systems which are at concept stage.

As expected food waste digestion (with an associated gate fee) coupled with the commercialised upgrading system (UWS) required the least incentive to allow financial sustainability. The suggested minimum incentive was 0.13 €/m^3 equivalent to 13c/L diesel equivalent or 13€/MJ. Power to gas on the other hand required a minimum incentive of 0.40 €/m^3 (UPG) an addition of 27c/l diesel equivalent. This is a limited market and on its own is of insufficient scale to supply a new green gas industry.

The abundant feedstocks from agriculture in the rural scenarios required larger incentives of between 85 and 103 €/MWh. As modelled in this scenario Power to Gas upgrading (RPG) yielded the lowest required incentive. The reason for this is almost half the feedstock is sourced from electricity as opposed to feedstocks, which are either weak in methane potential and voluminous (slurry) or need to be purchased (grass silage). This is a crucial output: Hydrogen upgrading when the hydrogen is sourced from electricity via electrolysis can be economically competitive when the feedstock in the biogas facility is expensive (grass silage) or has a low specific methane yield (slurry).

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Supplementary Files

The outputs of the simulations were attached as supplementary materials facilitate the transparency and reproduction of the work.

Conflict of interest

The authors declare no conflicts of interests.

Abbreviations

AD – Anaerobic digestion
BMP – Biomethane potential
CS – Cattle slurry
DFC – Direct fixed capital
FW – Food waste
IRR – Internal rate of return
MTOE – Million tonnes of oil equivalent
OFMSW – Organic fractions of municipal solid waste
P2G – Power to gas
PBP – Payback period
ROI – Return on Investment
t – Tonne
TEA – Techno-economic analysis
TRL – Technology readiness level
TS – Total solids
VS – Volatile solids
wwt – wet weight tonne

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Table 1. Feedstocks used in different scenarios, their characteristics, BMP and costs.

Scenario	Composition	Capacity (t/yr.)	TS (%)	VS (%)	BMP (L CH_4/kgVS)	OLR (kgVS/m^3/day)	HRT (days)	Cost (€/t)	References
Urban	FW	100,000	29.4	28	470	3.0	30	-50*	[17, 18, 61, 62]
Rural	Grass silage	75,000	29.3	26.8	366	3.5	25	27	[19, 63, 64]
	Slurry	65,000	9.6	7.5				1. 4$^{\psi}$	[63, 65]
Coastal	Grass silage	50,000	29.3	26.8	347	3.5	25	27	[19, 63, 64]
	Slurry	45,000	9.6	7.5				2. 4$^{\psi}$	[63, 65]
	FW	2,000	29.4	28				-50*	[18, 61, 65]
	Seaweed	5,000	14.2	10.3				4$^{\psi}$	[24, 66]

*The negative costs indicate the tipping fee to discard organic wastes without landfilling.

$^{\psi}$ The cost here refers to the transportation of slurry or seaweed from production to treatment facility.

Table 2. List of assumptions used in this work.

Type	Assumption
Algae	10 €/t
Annual operating hours	7,920 h
Construction period	18 months
Depreciation method	Straight-line
Depreciation period	10 years
Digestate	0 €/t
Discount rate	7%
Income tax	12.5%
Inflation	4%
Insurance	1% on DFC*
Lifetime of the plant	20 years
Methane selling price	0.20€/m^3 STP
Salvage value	5%
Start-up costs	5% on DFC*
Start-up period	6 months
Working capital	1-month OPEX
Electricity	35€/MWh

*DFC – direct fixed capital

Table 3. Sizing and costing of different equipment used in different scenarios

	Unit Operation	Unit	Feedstock Type					
			Urban		Rural		Coastal	
			Size	Cost (€)	Size	Cost (€)	Size	Cost (€)
Upstream Section	Silo/Bin	m^3	392	65,000	297	65,000	225	65,000
	Screw Conveyor	m^3	15	36,000	15	26,000	15	18,000
	Shredder	t/h	13	104,000	10	94,000	13	86,000
	Centrifugal Pump	kW	1	15,000	1	16,000	0.75	14,000
	Pasteurization	m^3	28	37,000	30	40,000	21	27,000
	Heat Exchanger	m^2	2×61	152,000	2×68	164,000	97	100,000
	Storage Tank	m^3	2×140	292,000	2×150	312,000	2×103	220,000
	Digester	m^3	2×10,100	1,750,000	2×8,865	1,726,000	12,400	893,000
	Decanter	m^3	3×54	903,000	34	226,000	22	176,000
	Digestate	m^3	23,000	253,000	23,000	255,000	17,700	247,000
	Upstream (A)		Urban	3,607,000	Rural	2,924,000	Coastal	1,846,000
Water Scrubbing			UWS		RWS		CWS	
			Size	Cost (€)	Size	Cost (€)	Size	Cost (€)
	Centrifugal Pump	kW	7	34,000	7	34,000	7	35,000
	Centrifugal Pump	kW	1	15,000	1	15,000	1	15,000
	Compressor	kW	123	140,000	92	84,000	70	73,000
	Compressor	kW	16	61,000	11	61,000	8	61,000
	Compressor	kW	3	61,000	3	61,000	3	61,000
	Absorber	m^3	22	78,000	17	62,000	13	47,000
	Stripper	m^3	22	78,000	17	62,000	13	47,000
	Cooler	m^2	2	9,000	2	9,000	1.5	8,000
	Total WS (B1)			476,000		388,000		347,000
	Unlisted (C1)			1,021,000		828,000		548,000
	Net (A+B1+C1)		UWS	5,104,000	RWS	4,140,000	CWS	2,741,000
Microalgae			UMA		RMA		CMA	
			Size	Cost (€)	Size	Cost (€)	Size	Cost (€)
	Raceway Pond	m^3	4×4,995	340,000	3×5,000	252,000	2×5,800	190,000
	Centrifugal Pump	kW	2	20,000	1.3	17,000	1	16,000
	Clarifier	m^2	33	66,000	25	56,000	19	48,000
	Decanter	m^3/h	2,500	219,000	1,800	219,000	1.4	219,000
	Compressor	kW	115	131,000	84	80,000	62	68,000
	Compressor	kW	15	61,000	11	61,000	8	61,000
	Absorber	m^3	22	78,000	17	62,000	13	47,000
	Total MA (B2)			915,000		747,000		649,000
	Unlisted (C2)			1,131,000		918,000		624,000
	Net (A+B2+C2)		UMA	5,653,000	RMA	4,589,000	CMA	3,119,000

			UP2G		RP2G		CP2G	
			Size	Cost (€)	Size	Cost (€)	Size	Cost (€)
Power to gas	Desulfurizer	t/h	3	15,000	2	15,000	2	15,000
	Electrolyser	MW	2×9	1,438,000	2×7	1,378,000	10	731,000
	Catalytic methanation	m^3	4×2400	740,000	3×2400	555,000	3×2650	374,000
	Compressor	kW	368	387,000	268	289,000	197	217,000
	Total P2G (B3)			2,580,000		2,237,000		1,337,000
	Unlisted (C3)			1,547,000		1,290,000		796,000
	Net (A+B3+C3)		UP2G	7,734,000	RP2G	6,451,000	CP2G	3,979,000

Table 4. Different utilities used in various scenarios with their unit price.

		Unit price	Urban			Rural			Coastal		
	Unit	(€)	UWS	UMA	UP2G	RWS	RMA	RP2G	CWS	CMA	CP2G
Power	MWh	35	14,500	15,900	33,400	11,200	12,200	25,500	8,400	9,200	18,900
Steam	t	10.56	1,900	1,900	1,900	2,000	2,000	2,000	1,400	1,400	1,400
Cooling Water	t	0.04	430,200	425,100	7,322,100	263,400	257,400	5,469,200	182,800	176,100	4,013,200
Chilled Water	t	0.35	47,800	211,100		40,400	176,400		35,100	146,000	
El. Electrolyser	MWh	35			141,800			107,500			79,200
Steam (High P)	t	22			12,300			9,300			6,800

*All the values were rounded to the nearest hundreds.

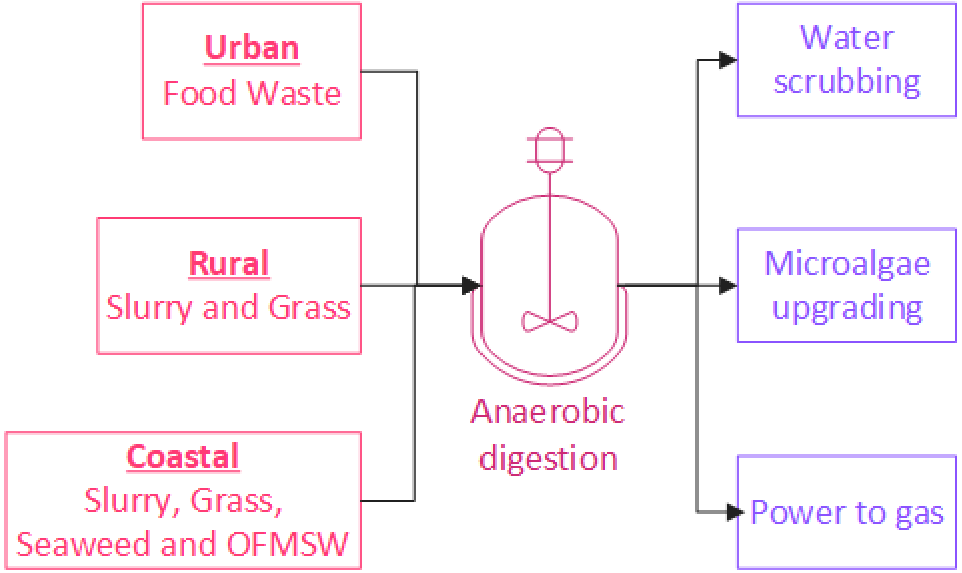


Figure 1. Schematic of nine scenarios used in this study in a combination of three feedstocks and three upgrading methods.

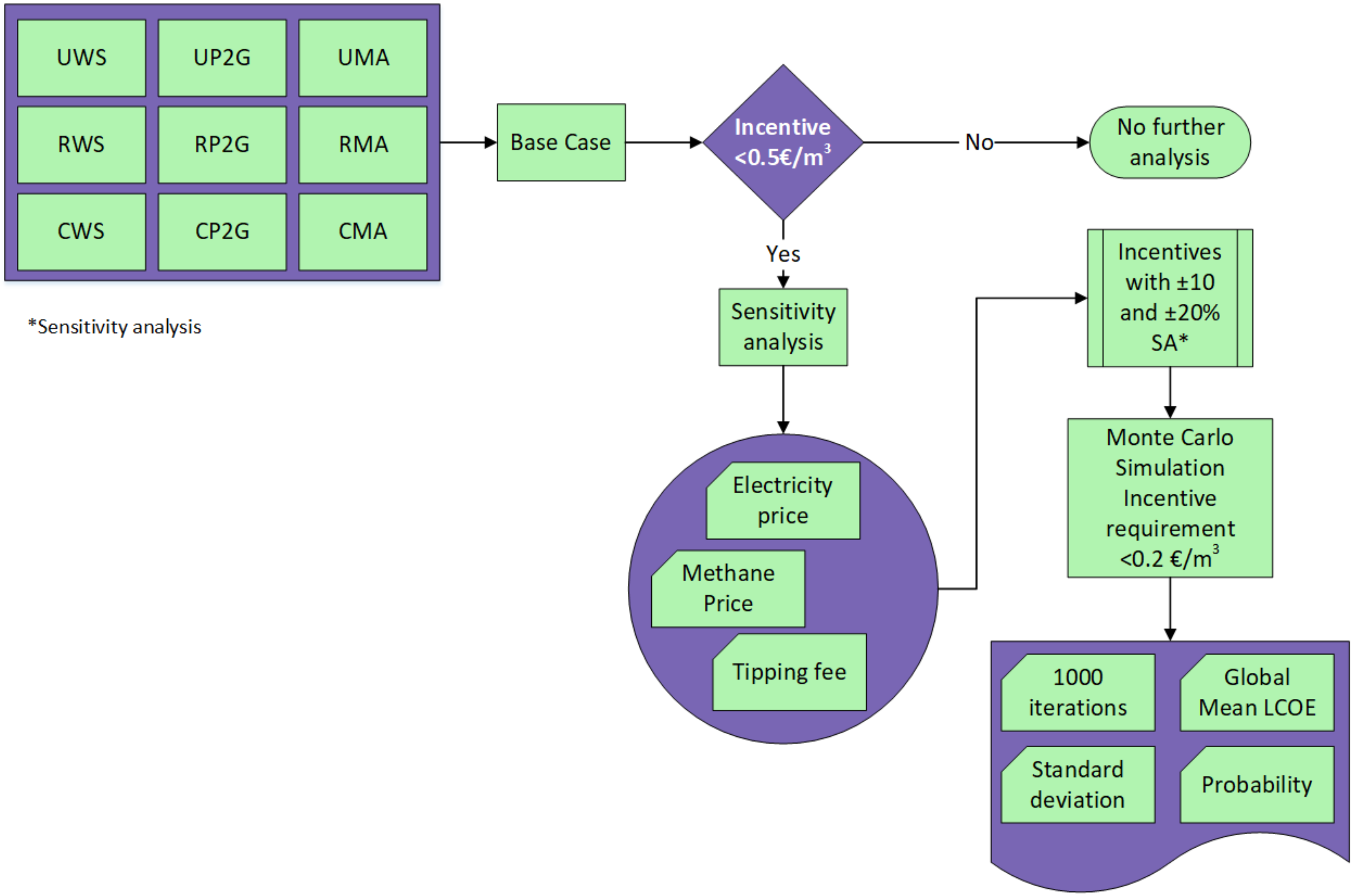
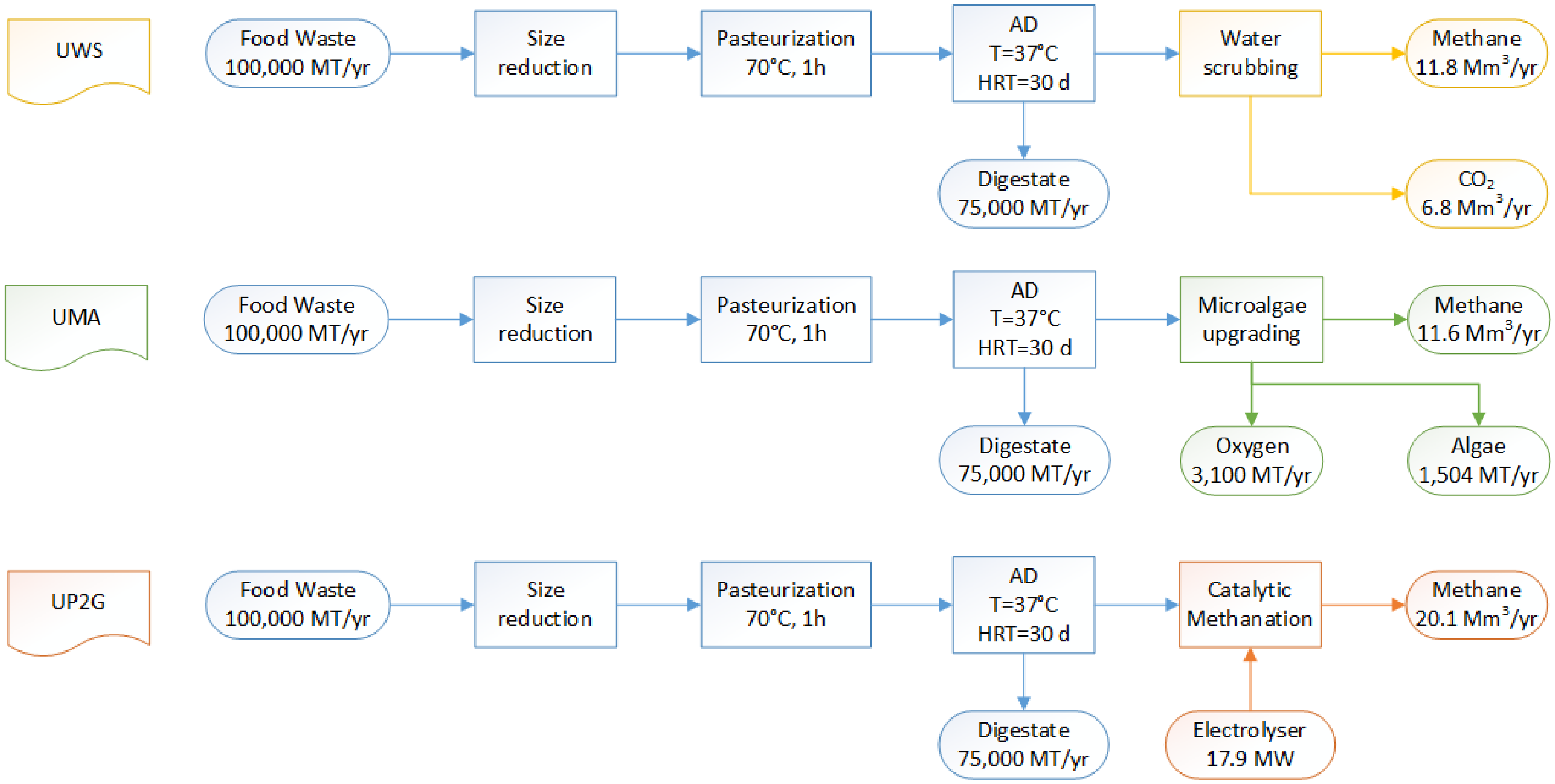
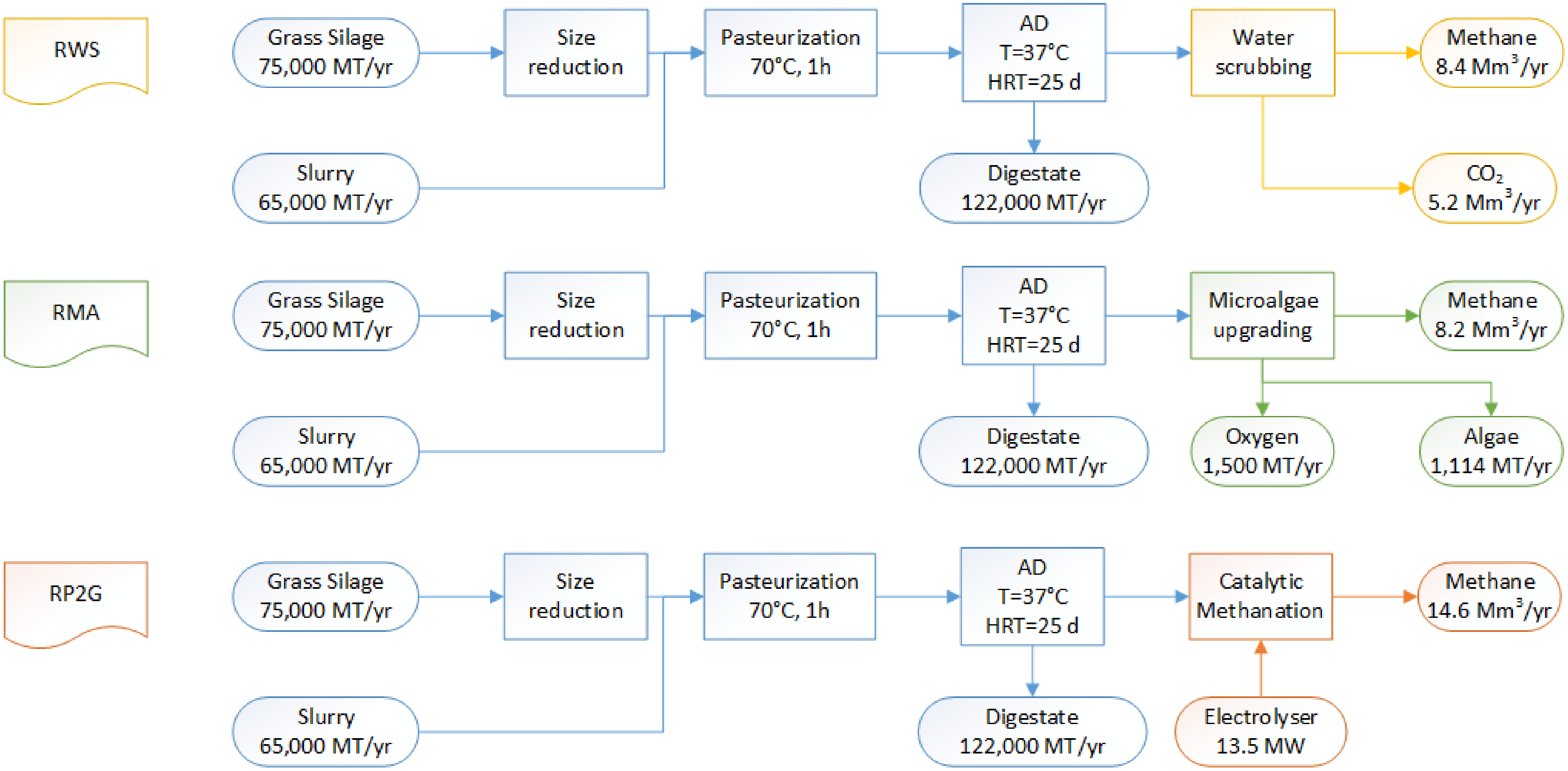
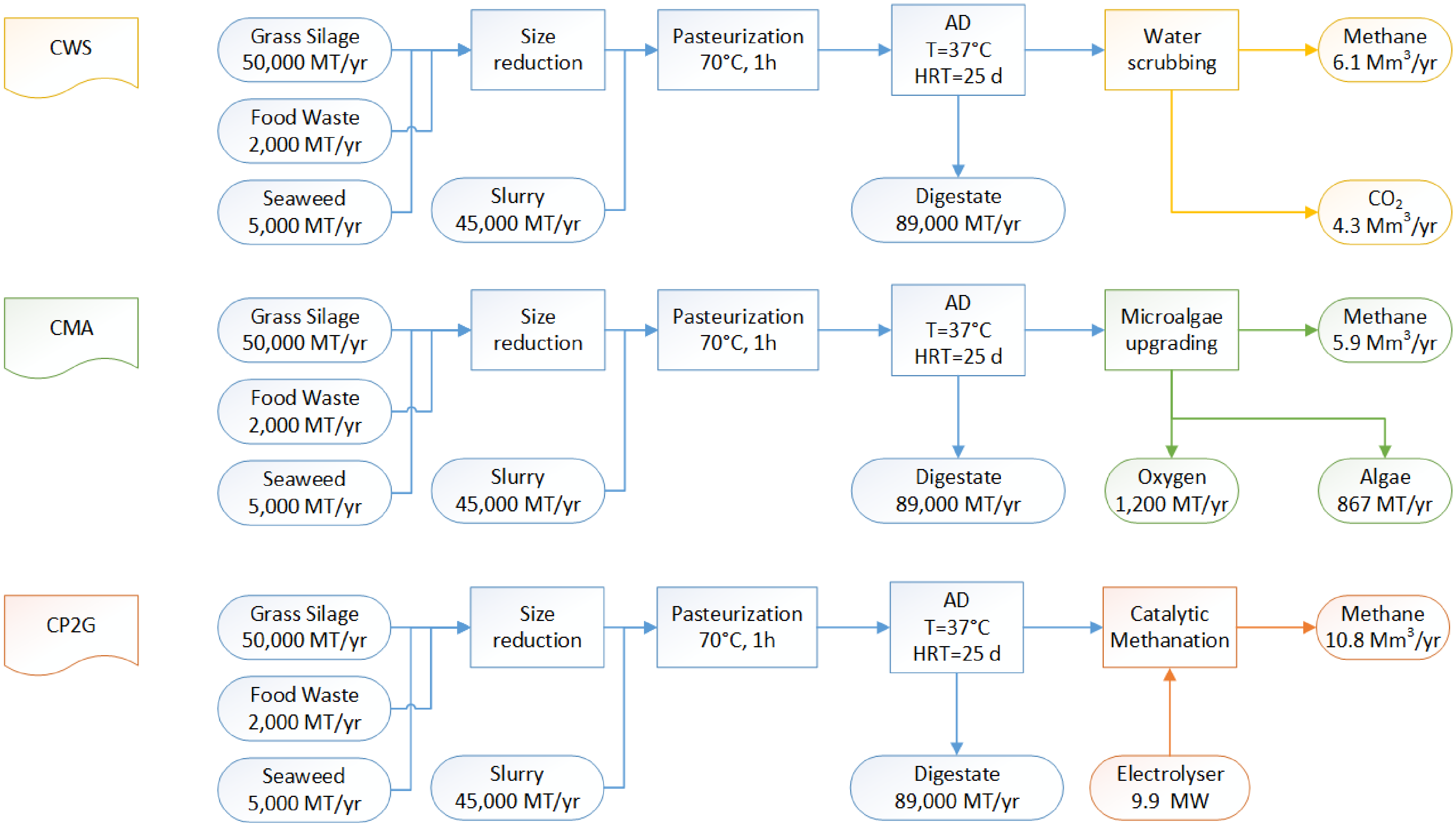


Figure 2. A systematic methodology to shortlist and undertake sensitivity analysis and Monte Carlo Simulation.


UWS
Food Waste 100,000 MT/yr
Size reduction
Pasteurization 70°C, 1h
AD T=37°C HRT=30 d
Water scrubbing
Methane 11.8 Mm^3/yr
Digestate 75,000 MT/yr
CO_2 6.8 Mm^3/yr
UMA
Food Waste 100,000 MT/yr
Size reduction
Pasteurization 70°C, 1h
AD T=37°C HRT=30 d
Microalgae upgrading
Methane 11.6 Mm^3/yr
Digestate 75,000 MT/yr
Oxygen 3,100 MT/yr
Algae 1,504 MT/yr
UP2G
Food Waste 100,000 MT/yr
Size reduction
Pasteurization 70°C, 1h
AD T=37°C HRT=30 d
Catalytic Methanation
Methane 20.1 Mm^3/yr
Digestate 75,000 MT/yr
Electrolyser 17.9 MW


RWS
Grass Silage 75,000 MT/yr
Size reduction
Pasteurization 70°C, 1h
AD T=37°C HRT=25 d
Water scrubbing
Methane 8.4 Mm^3/yr
Slurry 65,000 MT/yr
Digestate 122,000 MT/yr
CO$_2$ 5.2 Mm^3/yr
RMA
Grass Silage 75,000 MT/yr
Size reduction
Pasteurization 70°C, 1h
AD T=37°C HRT=25 d
Microalgae upgrading
Methane 8.2 Mm^3/yr
Slurry 65,000 MT/yr
Digestate 122,000 MT/yr
Oxygen 1,500 MT/yr
Algae 1,114 MT/yr
RP2G
Grass Silage 75,000 MT/yr
Size reduction
Pasteurization 70°C, 1h
AD T=37°C HRT=25 d
Catalytic Methanation
Methane 14.6 Mm^3/yr
Slurry 65,000 MT/yr
Digestate 122,000 MT/yr
Electrolyser 13.5 MW



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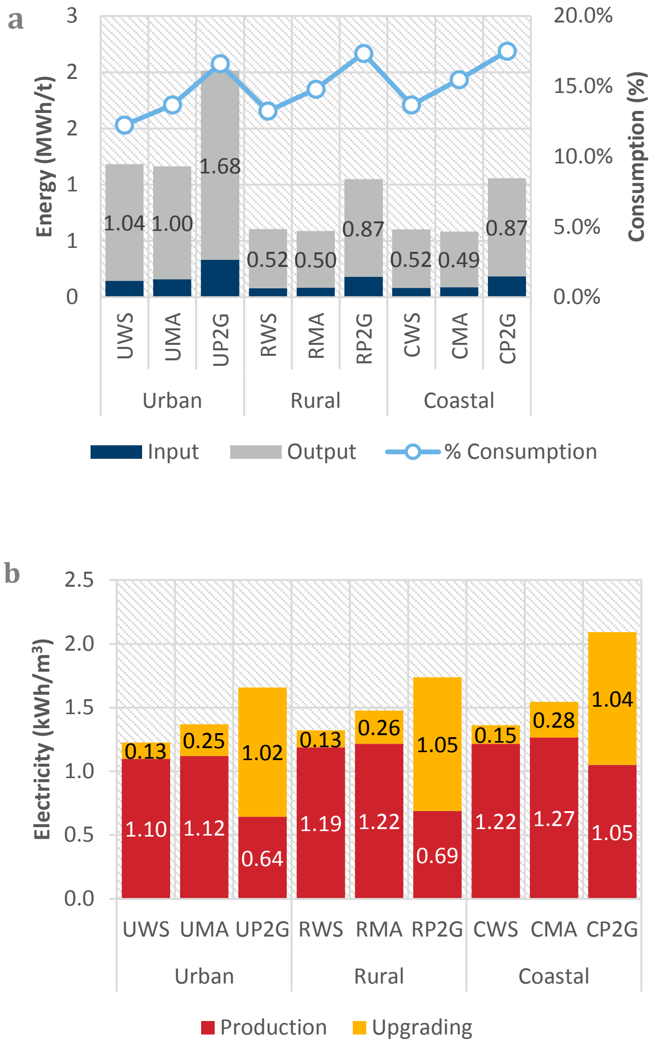

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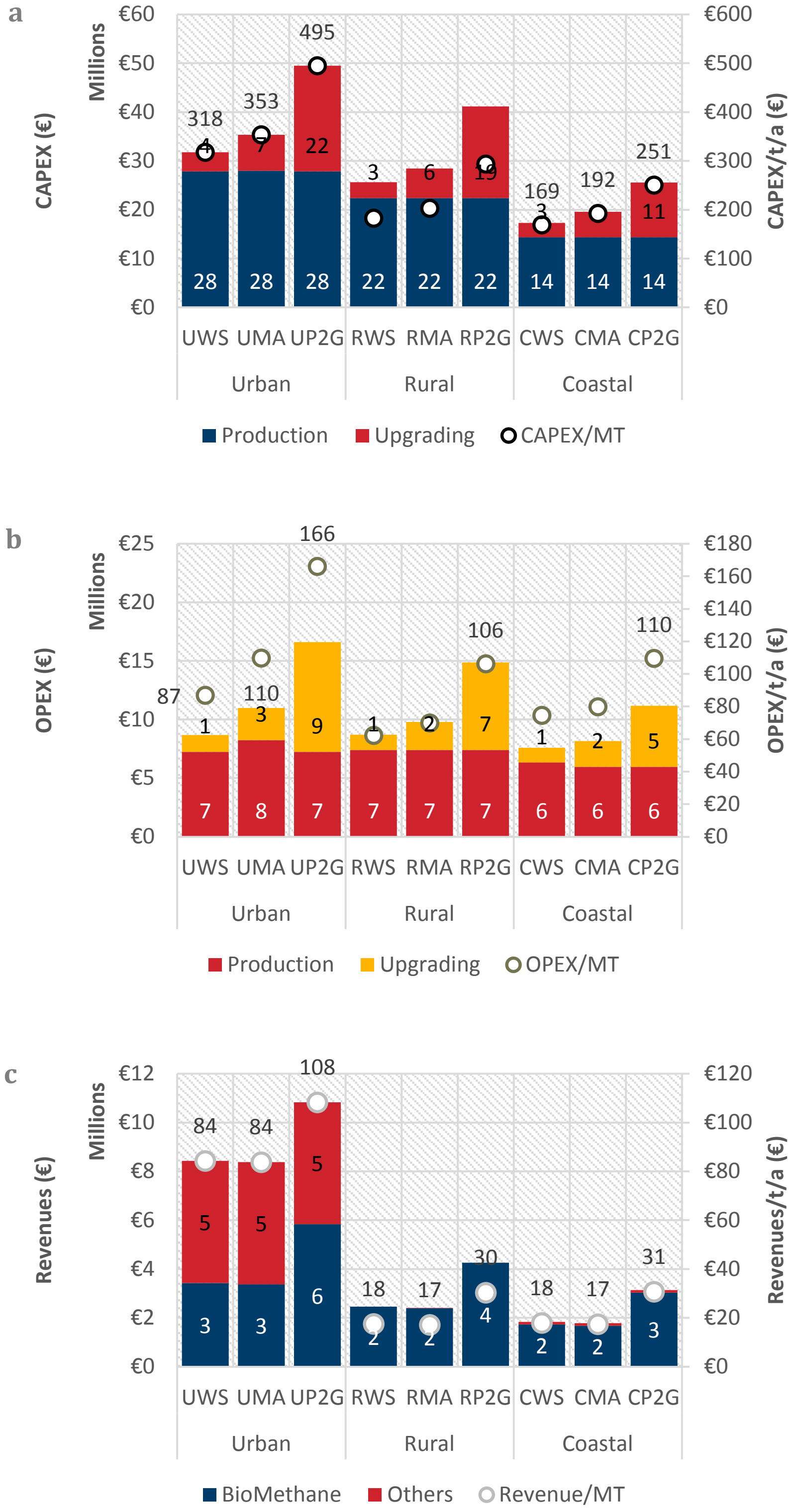

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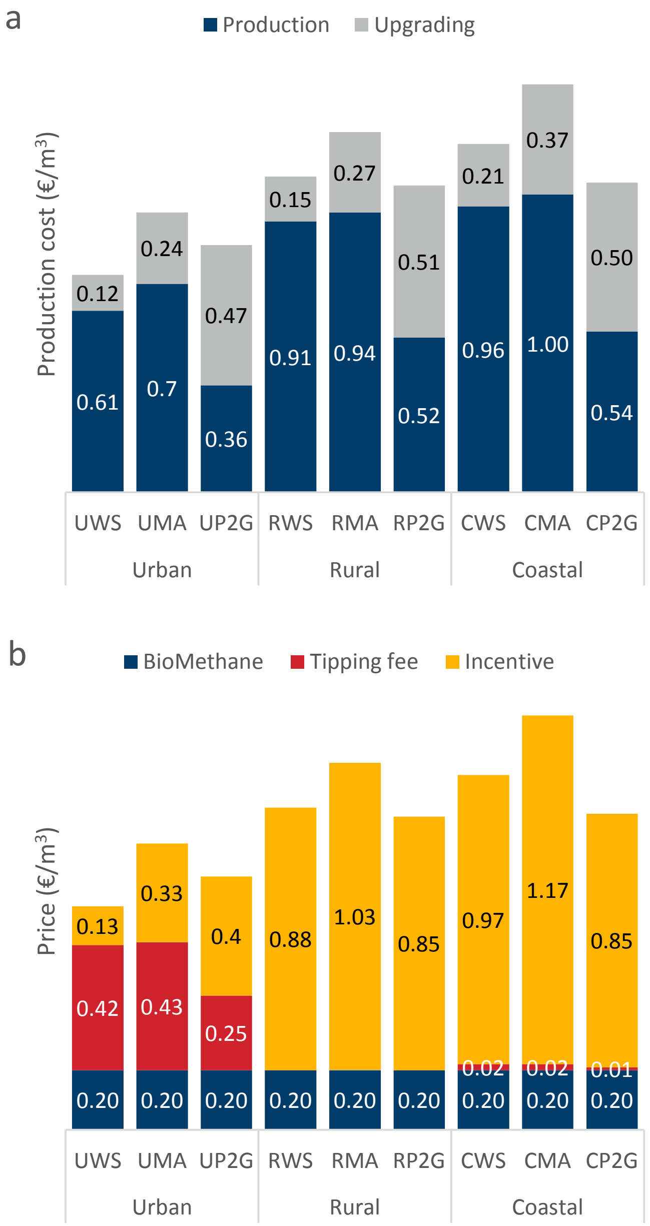

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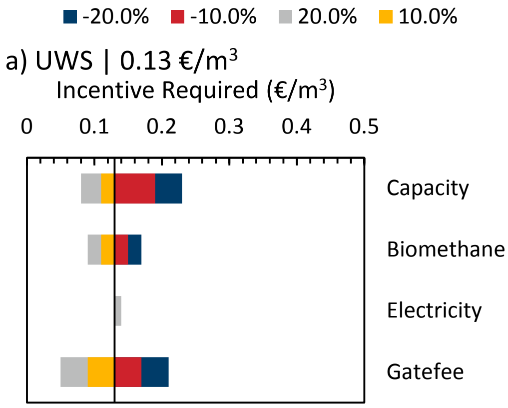
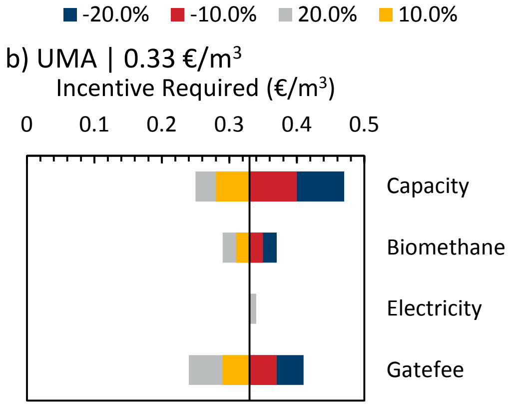
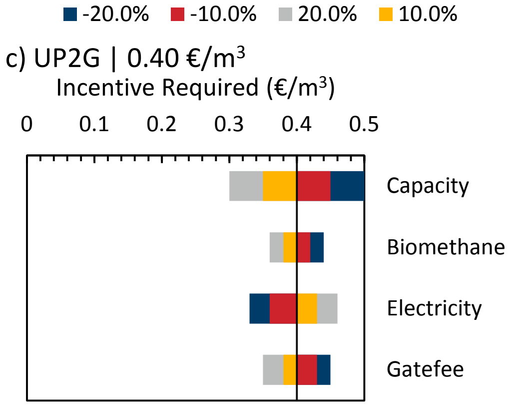


a) UWS | 0.13 €/m^3

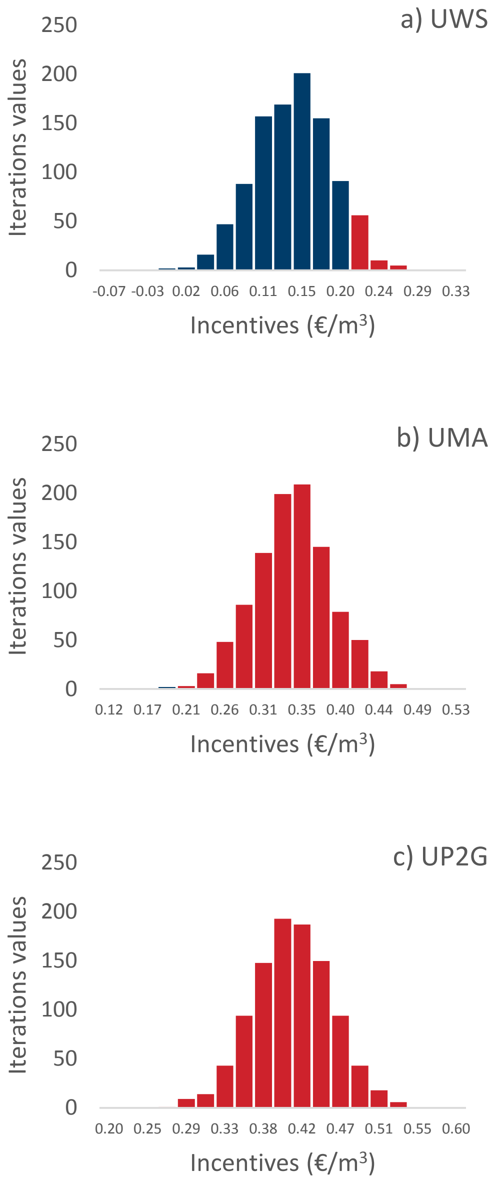


b) UMA | 0.33 €/m^3



c) UP2G | 0.40 €/m^3

Figure 7. Sensitivity analysis of the urban scenarios on factors that affect the incentives.



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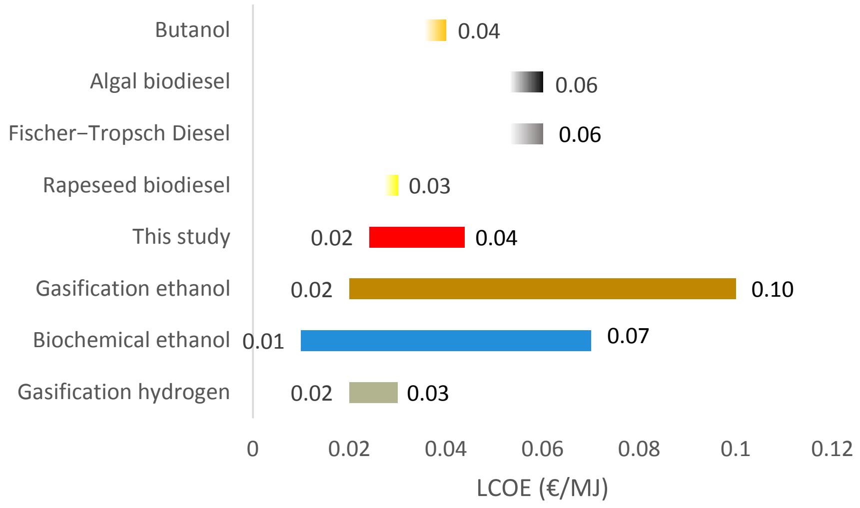

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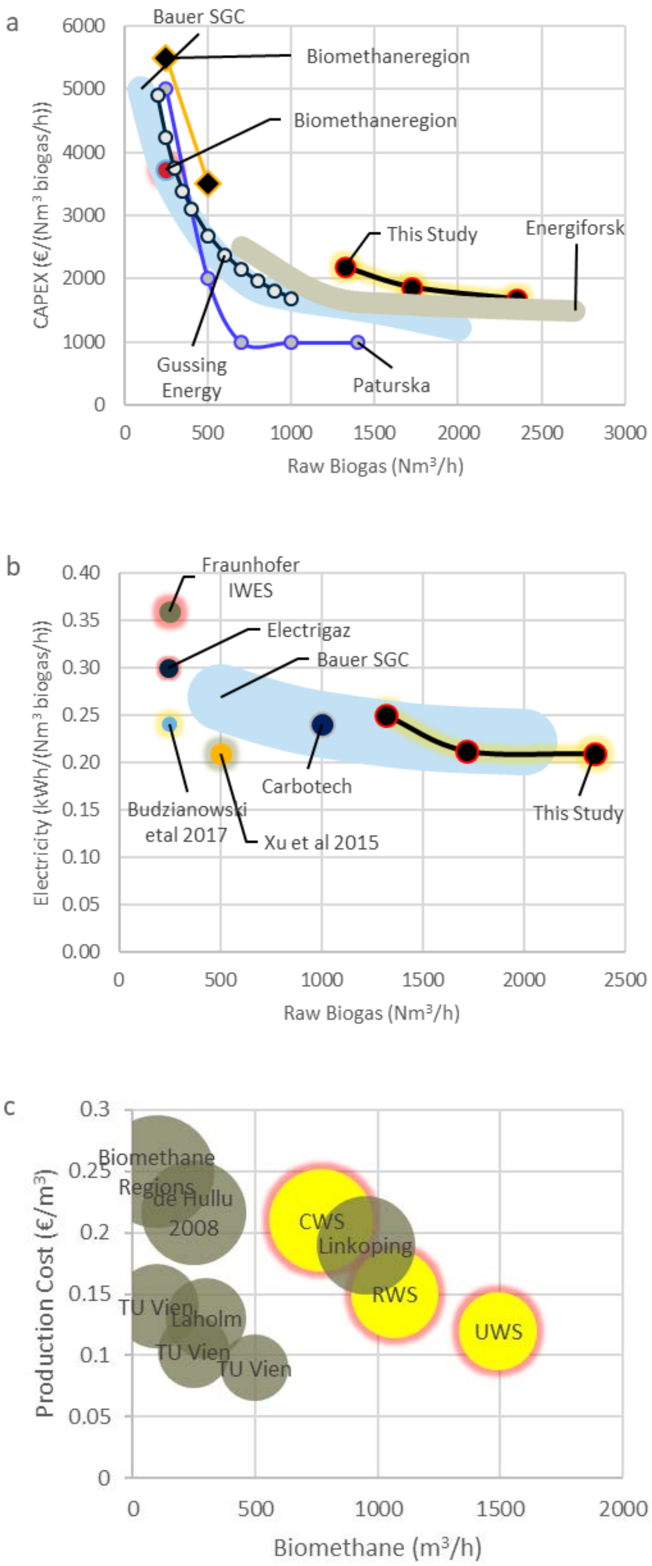

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