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Techno-economic Feasibility Assessment of Renewable Electrical and Thermal Energy Supply Options for Biomethane Production Plants

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Abstract

Bioenergy, solar energy and geothermal energy are among the most important types of renewable energy sources, which contribute to a more efficient energy use, climate change mitigation, and environmental protection. Upgrading biogas to biomethane production has become one of the most interesting targets in recent years, as a proper alternative source for fossil fuels. Despite this method is highly efficient process, it requires a high thermal energy demand for anaerobic digestion in addition to more required electricity required for upgrading biogas into the biomethane.

This study investigates two methods of utilizing biogas: converting the total biogas into the biomethane and converting a portion of the biogas into the biomethane and the remainder is used in a combined heat and power (CHP) generation. The energy demand of fully biomethane production plants is supplied by the national grid, a heat pump, photovoltaic panels system, and combination of a heat pump and photovoltaic panels (scenarios one to four). The energy demand for the combination of and biomethane production plants is supplied by a combination of CHP generation and a heat pump or a combination of CHP generation and a biogas boiler (scenarios five and six).

Organic fraction of municipal solid waste (OFMSW), livestock, wastewater sludge (WWS) and mixture of different feedstocks are considered as different feedstocks for each of the mentioned scenarios. The feedstocks need various electrical and thermal energy demand considering different biomethane productivity per unit of feedstocks mass (BMP).

Economic analysis is also conducted to determine the most efficient scenarios and feedstocks for biomethane production based on different electricity prices: typical electricity prices of Italy and France.

The results show that employing a heat pump and photovoltaic panels system are a viable and efficient technology for the typical electricity price in Italy. However, employing photovoltaic panels system is not recommended for typical electricity cost in France, due to the high cost of photovoltaic panels systems instalments and maintenances compared to the electricity price of France.

1 Introduction

Reducing energy consumption as a part of 2050 EU decarbonization targets has been set to use more efficient energies, which result in less energy consumption, climate change mitigation and environmental protection. Earlier renewable energy directive RED (2009/28/EC) was revised and implemented in 2018, due to the importance of renewable energy (1,2). EU supports countries and stake-holders to invest, promote and collaborate in the field of renewable energy in order to meet 2030 EU targets regarding increasing energy efficiency, more renewable energy use and reducing greenhouse gas emissions (1,3).

The limited source as well as environmental and economic impacts of fossil fuels consumption give opportunity to use alternative sources with less harmful effects on ecosystem and to be cost effective (4). Bioenergy, solar energy and geothermal energy are among the most important types of renewable energies which contribute to reduce greenhouse emissions and to maintain ecosystem services (5).

Biomass as a type of renewable energy provides an efficient alternative source of renewable energy rather than fossil fuels in transportation field (biofuel). The anaerobic digestion of organic material also leads to the production of biogas that can be used to generate thermal and electrical energy (5,6).

1.1 Anaerobic digestion

Anaerobic digestion (AD) is a microbial process that occurs in absence of oxygen. This process is harnessed to efficiently break down organic fraction of materials such as agricultural residues, food wastes, and animal manure to produce biogas and nutrient-rich digestate (6). Biogas generally consists of 50-70% methane (CH_4), 30-50% carbon dioxide (CO_2) and small fractions of hydrogen sulphide (H_2S), ammonia (NH_3), nitrogen (N_2) and vapour water (H_2O) (7,8). All gasses in biogas exception of methane are considered as unwanted gasses or biogas pollutants. The energy content of gasses contained in biogas is characterized by low heating value (LHV). LHV of methane is 36 $\frac{MJ}{m^3 - CH4}$ at STP condition (9). Apart from methane, the higher concentration of other gasses (CO_2, H_2S, …) will result in reduction of biogas LHV. The average LHV of biogas contained 60-65% methane is approximately 20-25 $\frac{MJ}{m^3 - biogas}$ (9).

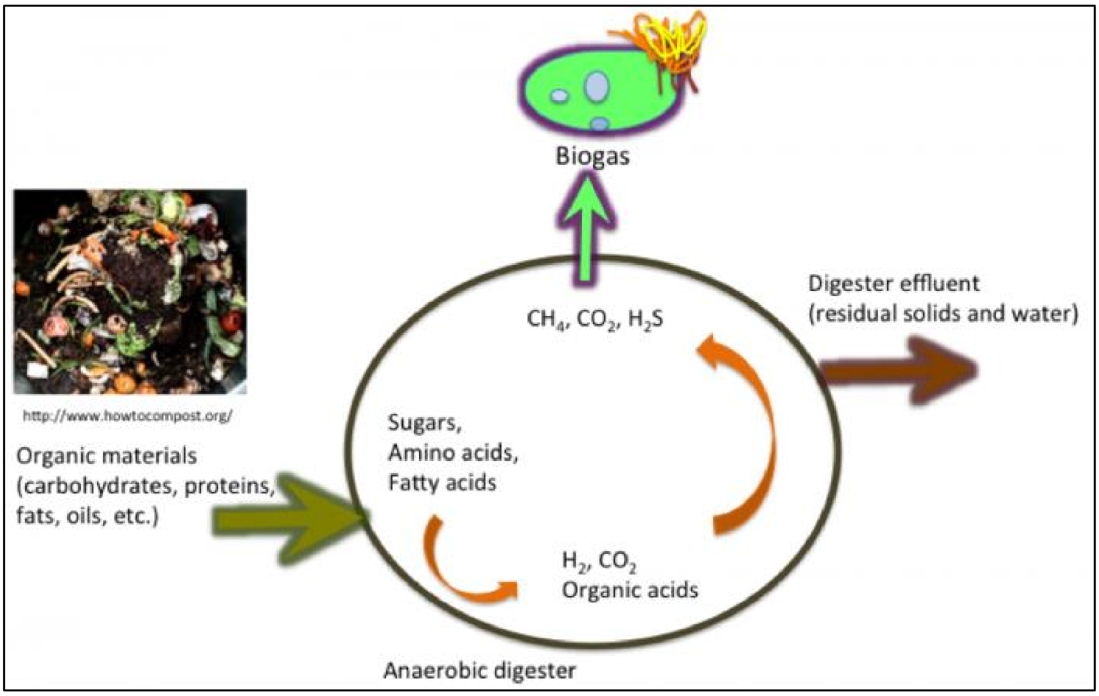

Figure 1. Input and output of the anaerobic digestion (10)

The AD process is affected by different parameters such as PH, temperature, retention time, etc (11,12). Temperature plays a crucial role in AD process, that can occur in three temperature conditions, psychrophilic (10–30 °C), mesophilic (30–40 °C), and thermophilic (50-70 °C) (12,13). This process is an acidic reaction at temperature less than 30°C, which causes less biogas production. Also, methanogenic bacteria results in reduction of biogas production at temperature above 70°C (12). Mesophilic condition at temperature 37°C is considered as the desired temperature condition in this study.

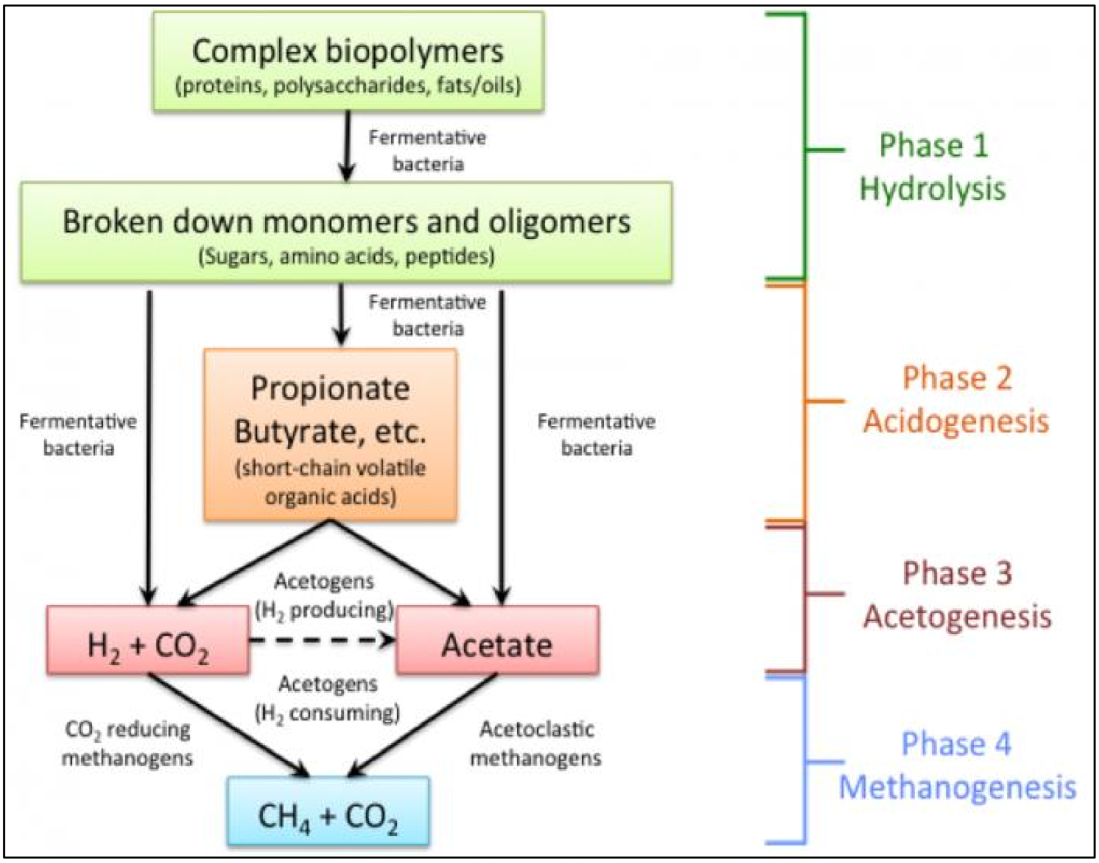

Figure 2. Phases of the anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (10)

There are four phases over anaerobic digestion process in order to convert organic matters into the biogas. The first phase is called hydrolysis, where non soluble complex biopolymers convert into the soluble organic matter that are more digestible and degradable. The second phase is acidogenesis step, where the soluble organic matters are broken down into short-chain volatile fatty acid and carbon dioxide in the presence of fermentative bacteria. The soluble organic matter from output of phase one can be converted into the hydrogen and carbon dioxide or acetate in the third phase that is called acetogenesis. Acetate or hydrogen and carbon dioxide convert into the methane and carbon dioxide in the phase of methanogenesis (10).

1.2 Uses of biogas

Biogas can be used in biomethane production plants, fuel cell, direct and indirect combustion and for generation of electricity and production of heat in combined heat and power generation (CHP). CHP is an energy-efficient method of electrical and thermal energy production that can be used to supply energy demand of AD process. The components of CHP generation include the primary mover which drives the system, heat recovery equipment, generator, and electrical interconnection (14). Also biogas can be treated and upgraded in order to increase LHV of the biogas. The final gas product of biogas upgrading process is called biomethane that can be used as a renewable source for fossil fuels or natural gas (9).

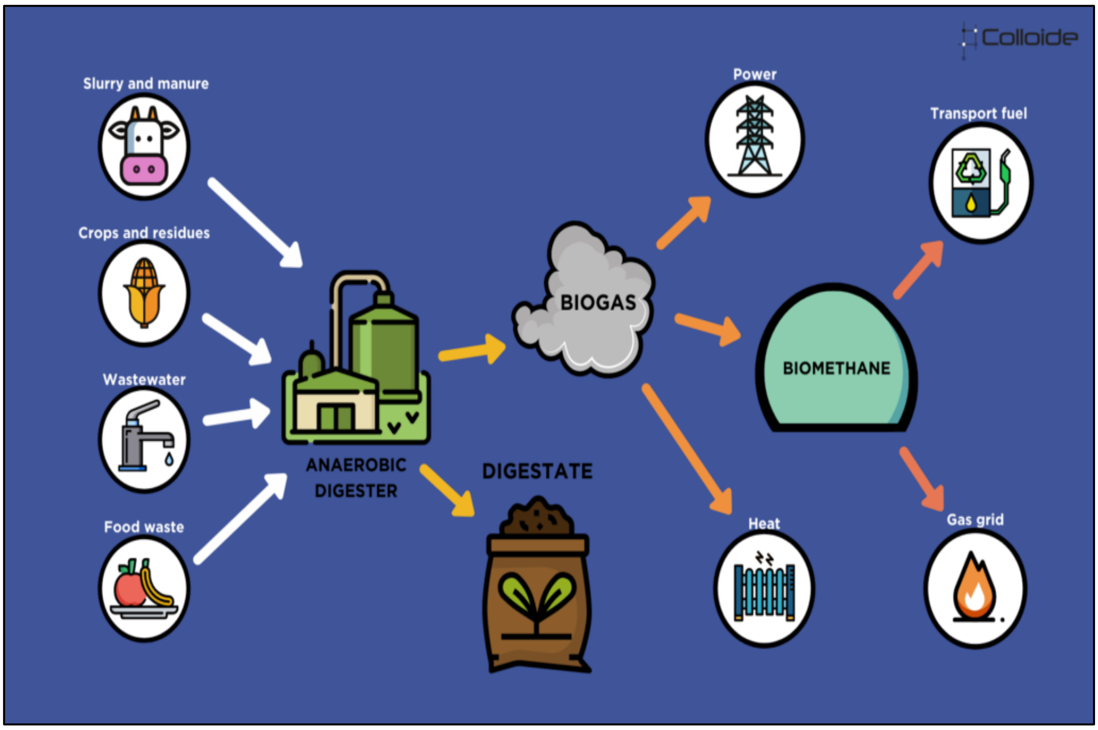

Figure 3. Possible feedstocks for biogas production and usage (15)

There are several biogas upgrading technologies including physical and chemical technologies such as water pressure scrubber, chemical scrubber, membrane separation pressure swing adsorption (PSA), and biological technologies such as in-situ, ex-situ and hybrid biological biogas upgrading. Biomethane production plants are emerging in the recent years in Europe (9). The share of physical and chemical technologies for biogas upgrading system is presented in Figure 4.

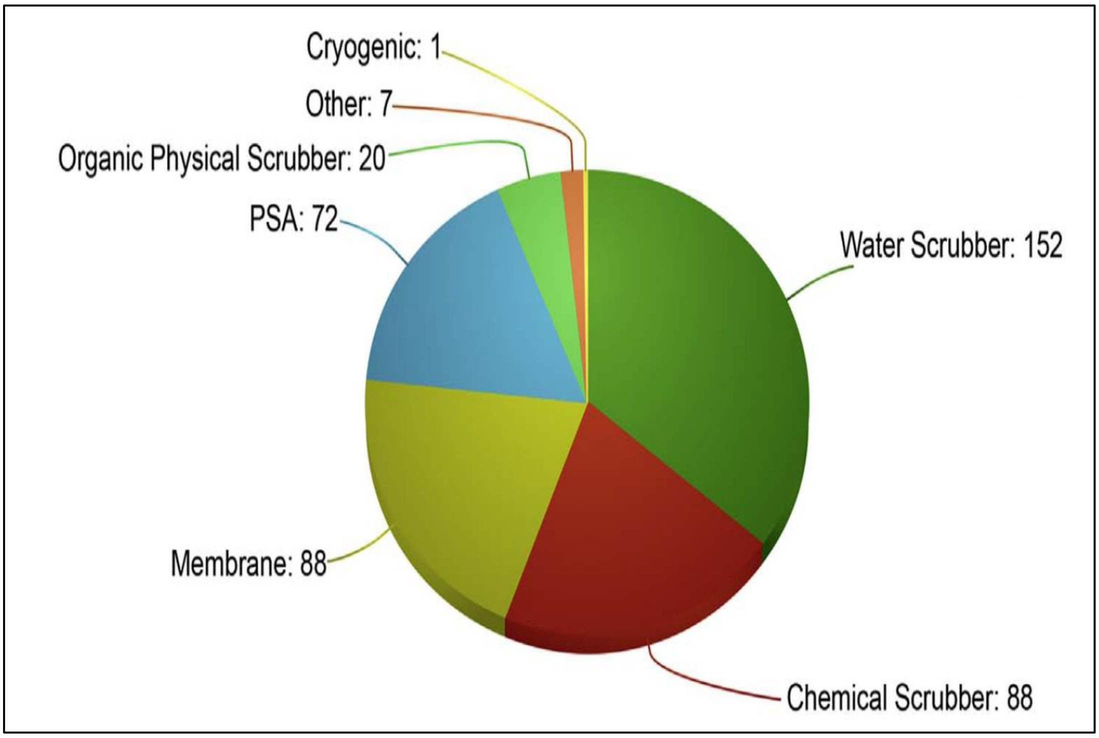

Figure 4. The share of biogas upgrading technologies (9)

Geothermal energy is another type of renewable energy with high eco-compatibility (16). The installation and use of geothermal systems (open-loop and close-loop) has generally experienced a large increase in the last decade (17). Open loop geothermal system refers to exploitation of earth energy through aquifer water abstraction through borehole. There are few parameters which affect open loop geothermal system design, including sink and source temperatures, heating demand and coefficient of performance (COP) of the heat pump depending on specific conditions (18). Solar energy technologies play a crucial role as well to achieve REPowerEU plan targets regarding less dependency on fossil fuels (18). Photovoltaic (PV) system is a method of electricity power generation by converting energy of sun through photovoltaic effect (19,20), with zero greenhouse gas emission in environment during the electricity generation, therefore this method helps EU to achieve carbon-neutrality targets by 2050 (21,22). Several parameters affect electrical energy generation by PV panels such as type of PV materials, solar radiation intensity, cloud and other shading effects, inverter efficiency, dust, module orientation, weather conditions, geographical location, cable thickness, etc (23). To understand how much energy can be provided by a single panel, the irradiance is multiplied by the panels areas, performance ratio, and then efficiency. The results show the monthly quantities of energy generation by a panel, depending on the irradiance coming from the sun (24,25).

This study presents the feasibility assessment of biomethane production plants and CHP generation plants, which are fed by four various feedstocks: organic fraction of municipal solid wastes (OFMSW), livestock, wastewater sludge and mixture of different feedstocks. These feedstocks are investigated across different scenarios for thermal and electrical energy generation, as well as purchasing energy from the national grid for the four plants, and comparing them from an energetic and environmental point of view. The cost analysis for each scenario is conducted considering Capital Expenditures (CapEx) include the CHP generation, construction and instalment of digesters, a heat pump, the upgrading system, the boiler and the PV plant costs. Also, the Operational Expenditures (OpEx) include the components maintenance and the electricity and heat costs from national grid, are computed for all scenarios and feedstocks. In this study, tariffs of 200 €/MWh_{el} and 130 €/MWh_{el} for electricity price are considered for the case study of Italy and France, respectively.

2 Case studies

This study considers a number of case studies of anaerobic digestion plants for biomethane production, which are hereby described. The aim of this study is to analyse the techno-economic feasibility of different renewable energy options to cover the heating and electricity needs of the plants hypothesized.

The plants are characterized by different feedstocks (section 2.1) and different hypotheses on the coverage of heating and electricity needs (section 2.2). Based on the quantity of feedstock supplied, the digester was sized (section 2.3).

2.1 Feedstocks

Co-digestion refers to mixing and treating two or more organic wastes simultaneously. It has several benefits compared to mono digestion of feedstocks, such as higher biogas production and consequently higher quantity of biomethane production (7). This results from carbon-to-nitrogen (C/N) ratio balance, synergetic effects of microorganism and dilution of few inhibitory substances like ammonia (26). Also, there are some problems to use co-digestion such as feedstocks transportation cost (27).

In this study, four different feedstocks are considered as the primary inputs for anaerobic digesters, where these undergo a controlled decomposition process.

1. Organic Fractions of Municipal Solid Waste (OFMSW): consists in the organic matters received from the food waste, kitchen waste, leaves and yard waste and grass clippings. The total input is considered approximately 35,000 tons/year of OFMSW (28).
2. Livestock effluents (animal-based matters): consists in the pig slurry and cattle manure. For the second plant, the total input is considered approximately 42,300 tons/year of livestock effluents (29).
3. Wastewater sludge (WWS) from wastewater treatment plants (WWTPs). For the third plant, the total input is considered approximately 168,000 tons/year of wastewater sludge (30).
4. Mixture of different feedstocks: consist in 40% pig manure,15% poultry manure, 20% water, 5% silage corn, 5% triticale, 3% wheat flour, 3% waste milk, 3% corn flour, 3% onion and 3% fruit scraps. The total input for the fourth

plant is assumed approximately 36,500 tons/year of different feedstocks. This plant feedstock input is taken from a project presented in Lombardia (Italy).

The compositions of different feedstocks are presented in Table 1.

Table 1. Characteristics of feedstocks

Feedstocks	Input (t/y)	TSS (%wt.)	VS (%)	BMP (Nm^3/t)
OFMSW	35,000	23.0	81.6	75.6
Livestock effluents	42,340	6.9	74.9	14.0
Wastewater sludge	167,900	10.5	70.5	26.0
Mixture	36,500	22	90	49.2

2.1.1 Biogas and Biomethane productivity

The quantity of biogas production from AD process is function of volatile solids fed to the reactor, the removed volatile solids after anaerobic digestion process and the operating conditions of process (31). Total biogas productivity of process is considered 99.7%, considering 0.3% loss fraction of biogas from digesters (29,32). Biomethane can be used instead of natural gas without any change in designing as a flexible fuel (33). Also, biomethane can be produced by upgrading biogas, which approximately covers 90% of total biomethane production in the world (34,35). Methane accounts for approximately 60% of biogas volume, which is transformed into biomethane through upgrading (31). Based on highest literature values regarding membrane field, methane losses is 1.4% of its volume over upgrading phase (29,32). The daily net biogas and biomethane production (in fully biomethane production plants configuration) are presented in Table 2.

Table 2. Net daily biogas and biomethane production in AD plants

Feedstocks	Net biogas production (Nm^3/d)	Net biomethane production (Nm^3/d)
OFMSW	11,930	7,130
Livestock effluents	2,470	1,600
Wastewater sludge	17,650	11,780
Feedstocks mixture	8,145	4,840

2.2 Configurations and scenarios

This study presents two methods of using biogas: the first consists in converting the total biogas to biomethane and the second sends a portion of the biogas into CHP plant and upgrading the rest. The study investigates six possible scenarios for thermal and electrical energy generation, as well as purchasing energy from the national grid for the four plants, and comparing them in terms of energetic, environmental and economic.

The possible scenarios are listed below:

1. The first scenario represents the fully biomethane production plant, where the total required heat demand is supplied by a gas boiler, and the electricity required for the upgrading is supplied by the national electricity grid.
2. The second configuration represents the fully biomethane production plant, where the total required heat demand is supplied by a heat pump and the required electricity demand of the upgrading system, stirring and a heat pump is sourced from the national electricity grid.
3. The third scenario represents the fully biomethane production plant, where the total required heat demand is supplied by a gas boiler (burning natural gas sourced by the national grid), and a portion of the required electricity of the upgrading system and mixing is provided by photovoltaic panels system, and remaining electricity demand is supplied by the national electricity grid.
4. The fourth scenario represents also the fully biomethane production plant, where the total required heat demand is produced by a heat pump, and the required electricity of the upgrading system, stirring and a heat pump is supplied by the photovoltaic panels system and national electricity grid.
5. This scenario represents the combination of biomethane production and CHP generation plants, where the total required electrical energy of the upgrading system, stirring and a heat pump is supplied by the CHP generation, sized to provide 100% of the required electrical energy. A heat pump is covered any thermal needs, which is not supplied by the CHP generation.
6. The last scenario represents the combination of biomethane production and CHP generation plants, where the total required electrical energy of the upgrading system and stirring is supplied by the CHP generation plant, sized

to provide 100% of the required electrical energy. A biogas boiler is covered any thermal demands, which is not supplied by the CHP generation.

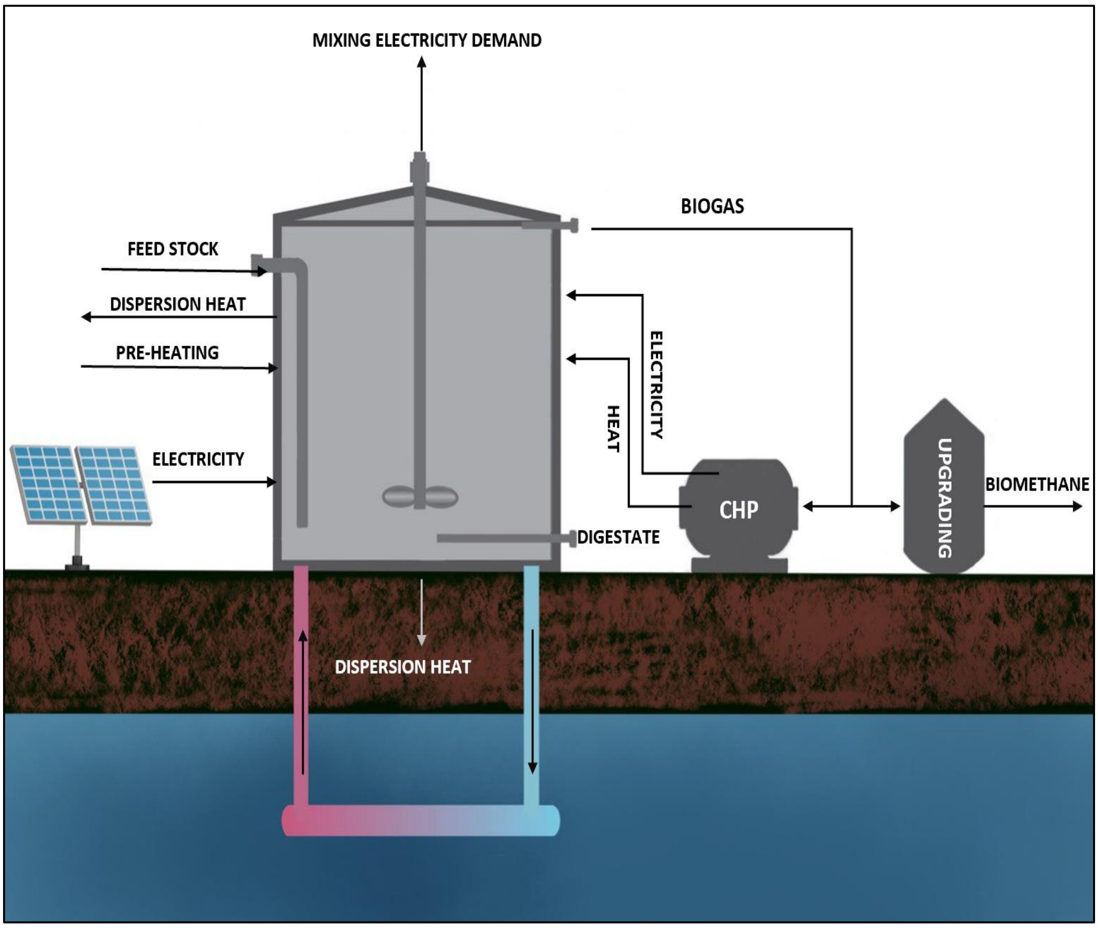

Figure 5. Schematic of overall energy demand and supply

2.3 Sizing of digesters

The digester volume term refers to the capacity and size of the digester vessels, typically measured in litres or cubic meters. The volume of a digester varies depending on its application and specific requirements (8). The digester volume is determined depending on various factors such as the type and the quantity of feedstocks being processed, the desired biogas production rate and the retention time needed for efficient digestion. The digester volumes can range from a few hundred to several thousand cubic meters in AD plants (36).

Digester vessels have a cylindrical shape and their dimensions are determined by few factors: the desired volume, available space, and structural considerations (29).

Mass of feedstock mixture (M), density of feedstock (ρ, assumed equal to the density of water), hydraulic retention time (HRT) and safety factor of anaerobic digestion process (SF=1.3) (37) are taken into account to determine reactors volume and head spaces for biogas production.

$$V = SF\left(\frac{M}{\rho}\right)HRT \qquad \text{Equation1}$$

As a result, the total volume of reactors, number of digesters and related characteristics are presented in Table 3.

Table 3. Geometric characteristics of digesters.

Characteristics/ Feedstocks	OFMSW	Livestock	WWS	Mixture
Reactor cylindrical volume (m^3)	7,480	9,048	35,880	7,800
Number of digesters	2	2	6	2
Active volume/digester (m^3)	3,740	4524	5980	3900
Digestion cylinder radius (m)	13	14	16	14
Digestion cylinder height (m)	7	7	8	7
Digestion cylinder walls area (m^2)	572	616	804	616
Digestion cylinder floor area (m^2)	531	616	804	616
Biogas dome volume (m^3)	4,600	5,747	8,579	5,747
Biogas dome radius (m)	13	14	16	14
Biogas dome height (m)	7	7	8	7
Biogas dome surface area (m^2)	1,062	1232	1,608	1,232
Total volume (m^3)	8,340	10,270	14,560	9,645

The lateral wall surfaces, floor areas and biogas dome surface areas are computed, as they are responsible for the heat losses towards the outside.

3 Energy balance of the digester

Thermal energy demand of anaerobic digestion process includes preheating thermal energy requirement of digesters (section 3.1.1), heat dispersions through digester floor slab, walls, and dome (section 3.1.2) considering meteorological data (section 3.1.3). Waste heat recovery from upgrading stage is also taken into account in order to reduce thermal energy demand of plant (section 3.2). The total required electricity of plant is computed (section 3.3). The feasibility assessment of CHP generation plant and photovoltaic panels to supply electricity demand of anaerobic digestion process and biogas upgrading stage are conducted (section 3.4). Also, energy balances for all scenarios and feedstocks are implemented (section 3.6).

3.1 Heating demand of plant

Heating demand of AD plant consists in the preheating of feedstocks to reach the operating temperature (mesophilic temperature, 37°C), and the fraction of heating loss from digesters (dispersion heat), that depend on the atmosphere, operating and feedstocks temperatures (30).

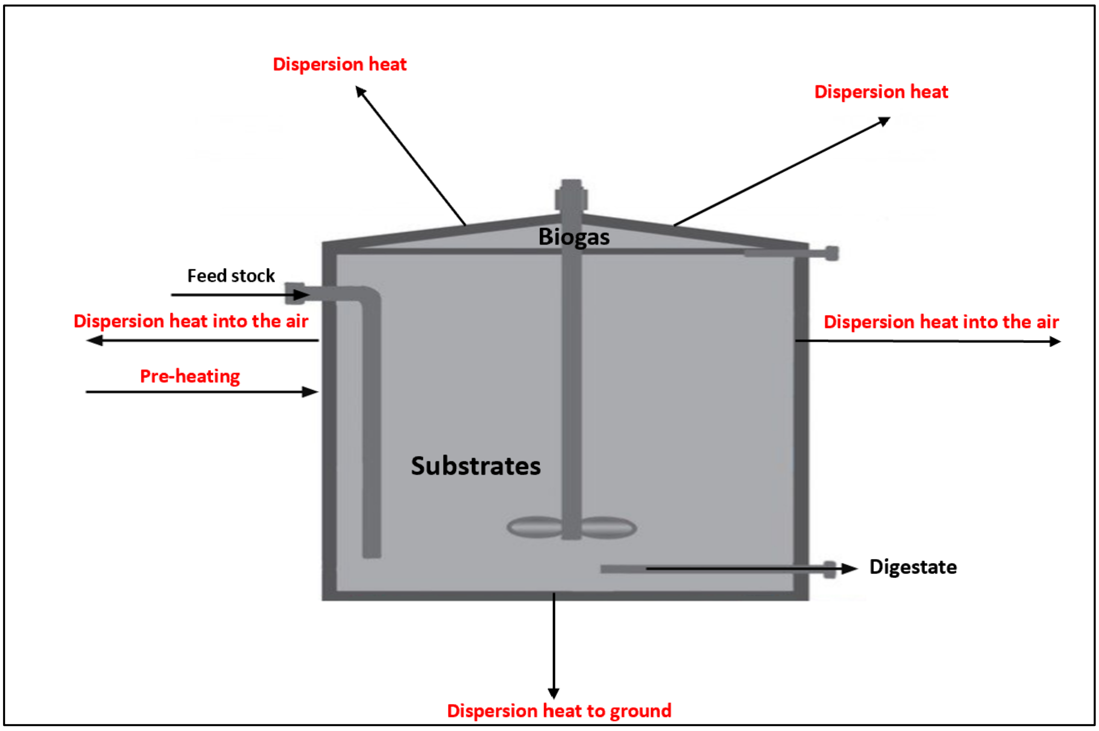

Figure 6. Digester heat losses towards the ground and the air

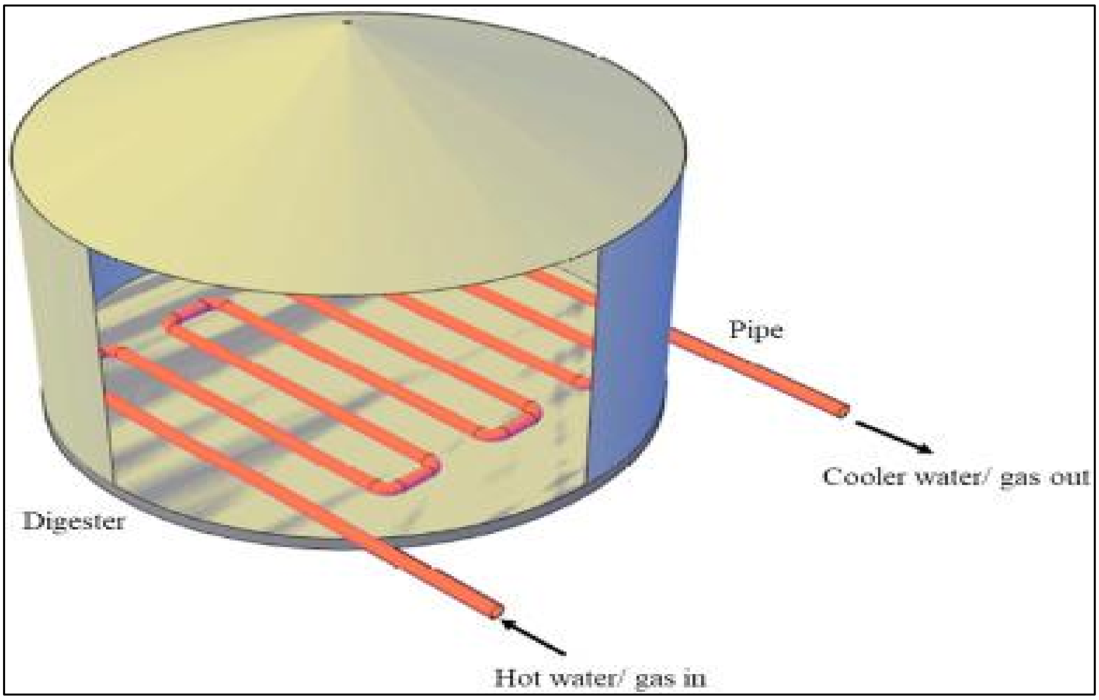

Figure 7. Digester heating system (38)

3.1.1 Preheating

The monthly energy demands of feedstocks preheating to reach operating temperature in AD plant (MWh_{el}/ month) are calculated with Equation 2.

$$Q_{ph} = M_d\, C_m\left(T_{dig} - T_f\right) \cdot D \cdot 24 \cdot 10^{-6}/3600 \qquad \text{Equation 2}$$

Where the operating temperature of digesters equals T_{dig}=37℃, the temperature of feedstocks is T_f=15℃, and the number of days in each month, the average specific heat capacity of feedstocks, and the total mass of feedstocks entered into each digester are D, C_m and M_d, respectively (29).

3.1.2 Heat dispersions through digester floor slab, walls, and dome

It is necessary to evaluate dispersion heat to ensure the same amount is provided to the digester to keep it at operating temperature.

This value is calculated for each month (MWh_{th}/month) with Equation 3.

$$Q_{loss} = \left[\pi {r_1}^2 \cdot U_{floor} + 2\pi r_1 h_1 \cdot U_{walls} + \pi\left({r_2}^2 + {h_2}^2\right) \cdot U_{dome}\right]\left(T_{dig} - T_{air}\right) \cdot D \cdot 24 \cdot 10^{-6} \qquad \text{Equation 3}$$

Where parameters are digester cylinder radius (r_1), biogas dome radius (r_2), transmittance values of floor (U_{floor}=0.465 W/m^2·k), the transmittance values of lateral walls (U_{walls}=0.32 W/m^2·k), the transmittance values of dome (U_{dome}=1 W/m^2·k), the digester cylinder height (h_1), the gasometer dome height (h_2) and the average monthly temperature (T_{air})(29).

The resulting preheating and dispersion heat of digesters, neglecting the value of obtained solar heat per year for different feedstocks, are presented in Table 4.

Table 4. Thermal energy demand of plants

Thermal energy demand	OFMSW	Livestock	Sludge	Mixture
Preheating (MWh_{th}/y)	895	1,083	4,295	933
Dispersion heat (MWh_{th}/y)	472	531	2,081	531
Total heating demand (MWh_{th}/y)	1,367	1,614	6,376	1,464

These values do not change depending on biogas consumption in next stages(29), while the installed thermal power changes depending on the technology used to supply the thermal energy demand of plant. This variation is influenced by the operating time of the heat pump, cogeneration plant, or gas boiler, which affects the plants investment cost.

3.1.3 Climatic data

It is necessary to determine the average atmospheric temperature at plant location to evaluate the precise quantity of heat demand of anaerobic digestion (AD) process to reach the mesophilic temperature through feedstock preheating and loss compensation. The PVGIS provides average temperature of various coordinates based on satellites information and meteorological data (24). Average monthly temperature at plant location with coordinates, 45.064°N latitude and 7.680°E longitude, is represented in Table 5 (24).

The aquifer temperature is considered equal to 16.4℃ at the depth of 15 m.

Geothermal heat pumps must be designed to ensure that the thermal demand is satisfied even in the worst climatic conditions, therefore the minimum temperature of Turin over a year based on highest literature articles, equal to $T_{ext,min}$=-8℃, is considered. It is necessary to use antifreeze solution to keep water temperature above 5 ℃ (39) to avoid freezing water in a heat pump. It is assumed the water temperature will stay constant from aquifer to surface by using appropriate equipment, grouting and installation.

Table 5. Average monthly temperature of Turin

Months	Temperature (℃)
January	3.4
February	6.2
March	7
April	13.1
May	16.6
June	19.5
July	23.5
August	23.4
September	18.5
October	11.4
November	8.1
December	2.6

3.2 Heat production

The plant releases waste heat in the upgrading stage, which is 0.13 kWh_{th}/Nm^3 of the biomethane production (29,32) that can be recovered and applied in order to reduction of the plant thermal energy demand for feedstock pre-heating and heat loss compensation. The heat demand, therefore, is partially covered by the upgrading phase waste heat, and the rest is supplied by gas boiler, a heat pump or CHP generation. Technical characteristics for these components are now listed. In the first and third scenarios, the capacity factor and efficiency of gas boiler are assumed 92% and 95%, respectively. Also, the same assumptions are considered for biogas boiler in scenario six. The capacity factor of a heat pump is assumed to be around 50% for operating time of 4380 hours per year in scenarios two, four and five. Furthermore, the CHP generation plant operates with a capacity factor of 92% and a thermal efficiency of 50% in scenarios five and six.

3.3 Electricity demand

The electricity demand of AD plant consists in required electrical energy for mixing feedstocks in anaerobic digesters, computed based on 5.8 W/m^3 of digester volume according to United States EPA (40). The optimal operating time condition is considered, as suggested in the literature, two hours per day with one-hour break between them (40).

Biomethane production from the conversion of biogas requires electrical energy for upgrading and compression stages (29). The electricity demand of upgrading and compression stages are estimated 0.3 kWh_{el}/Nm^3 and 0.4 kWh_{el}/Nm^3 of biomethane production, respectively(29,32). In this study, electricity demand of compression stage is neglected, because it is assumed that the plant is connected to the pipeline with sufficient pressure.

The heat pump electricity demand depends on the coefficient of performance (COP) of the heat pump. Assuming a geothermal heat pump is installed, the theoretical COP is defined as:

$$COP_{th} = \frac{273.15+T_{dig}}{T_{dig}-T_{ground}} \qquad \text{Equation 4}$$

Where T_{ground} is the average temperature of ground that remains constant over a year. According to literatures, real COP is considered to be half of the theoretical COP (41,42). The electrical energy consumption of the heat pump is computed as:

$$E_{el,HP} = \frac{Q_{th,HP}}{COP_{real}} \qquad \text{Equation 5}$$

Where $Q_{th,HP}$ is the thermal energy production by a heat pump.

3.4 Electrical energy production

Electrical energy demand is supplied by the national electricity grid with an assumed price of 200€/MWh_{el} (typical electricity price of Italy) in scenarios, one to five. Although, in scenarios three and four, it is partially generated by photovoltaic panels system. In scenarios five and six for the OFMSW feedstock, a portion of the electrical energy is supplied by national electricity grid to prevent extra generation of thermal energy by cogeneration plant.

3.4.1 Photovoltaic plant electricity generation

The SPR-MAX3-400 photovoltaic panel is selected to supply the electricity demand of the biomethane production plant in scenarios three and four. This choice is based on its efficiency of 22.6%, resulting in electrical energy generation that is 7% more than conventional panel at the same-sized arrays. A single panel has dimensions of 1.046 m and 1.69 m, which occupies an area of 1.767 m^2, with a nominal power of 400W (43).

Figure 8. Photovoltaic solar panels

Solar electrical energy generation of defined system is estimated by PVGIS-5 with following characteristics in Table 6 (25).

It is necessary to prevent excessive electrical energy generation by photovoltaic panels system due to the saving extra energy is impossible (in this case study). Therefore, July is considered as the reference month to determine the quantity of required PV panels, as it represents the minimum monthly electricity demand of the plant and the maximum monthly electricity generation of each panel, equals 57.5 kWh_{el}/month (25). Solar panels only generate electrical energy in specific day-time (operating time), between 10:00 and 16:00 based on the hourly average photovoltaic power output of the system in this case study (44). Hence, the average operating time of defined PV system is considered six hours per day over a year. Also, number of solar panels is planned to supply electricity demand of designed plant depending on feedstocks.

Table 6. Characteristics of the solar electrical energy generation system

Location	Turin
Database used	PVGIS-SARAH2
PV technology	Crystalline silicon
PV installed	0.4 kWp
System loss	14%
Optimum slope angle	40°
Optimum azimuth angle	1°
Yearly PV energy generation	532.52 kWh
Yearly solar irradiation	1761.02 kWh/m^2

3.5 Combined heat and power (CHP) generation

Combined heat and power (CHP), also known as cogeneration, is a high efficient low carbon heat production and electricity generation technology (45,46). CHP generation significantly is promoted by EU to improve energy efficiency in Europe (47). Using the CHP system increases supplying heat and power demand efficiency, while reducing emissions by 90% and 13-18%, respectively (48). The biogas utilization in CHP generation plants results in increment of bioenergy use and emission reduction, simultaneously(49).

The defined CHP generation plant is operated with an electrical efficiency of 40% and thermal efficiency of 50%, in scenarios five and six. The CHP system supplied electrical energy demand of the plant with burning a portion of the biogas. In scenarios five and six, the required biogas portion to supply the electrical demand of the plant by cogeneration system is determined through an iterative process.

The total thermal energy production by CHP system is determined according to:

$$Q_{CHP} = f_{CHP} \cdot M_{BG} \cdot LHV \cdot eff_{th} \qquad \text{Equation 6}$$

Where f_{CHP} represents biogas percentage in CHP system, M_{BG} indicates biogas production rate (Nm^3/y), eff_{th} determines the thermal efficiency of the CHP system (50%) and LHV illustrates low heating value of biogas (MJ/m^3). The LHV of biogas is determined by multiplying the LHV of biomethane (34.7 MJ/m^3) and CH_4 percentage of produced biogas.

The total electrical energy generation by CHP system is determined according to:

$$E_{CHP} = f_{CHP} \cdot M_{BG} \cdot LHV \cdot eff_{el} \qquad \text{Equation 7}$$

Where all of the parameters are consistent with the thermal energy production, except for eff_{th}, which represents the electrical efficiency of the CHP system (40%).

3.6 Results of energy balances

The electrical and thermal energy balances for each scenario are presented in following tables.

Table 7. Energy balance of scenario 1 (heating and electricity needs covered, respectively, with gas and electricity from the grid)

Feedstocks	OFMSW	Livestock	WWS	Mixture
Mixing electricity requirement (MWh_{el}/y)	354	428	1,700	370
Upgrading electricity requirement (MWh_{el}/y)	792	177	1,306	537
Total electricity requirement (MWh_{el}/y)	1,146	605	3,006	907
Waste heat production (MWh_{th}/y)	338	75	560	230
Gas boiler heat production (MWh_{th}/y)	1,029	1,539	5,816	1,234

The electrical energy demand of stirring is evaluated, which is constant for all scenarios. The upgrading electricity requirement and waste heat production also are consistent for scenarios one, two, three and four, as total produced biogas is converted to biomethane. Total heat demand is supplied by a gas boiler and total electricity demand is sourced by national electricity grid in scenario one.

Table 8. Energy balance of scenario 2 (heating and electricity needs covered, respectively, with heat pump and electricity from the grid)

Feedstocks	OFMSW	Livestock	WWS	Mixture
Mixing electricity requirement (MWh_{el}/y)	354	428	1,700	370
Upgrading electricity requirement (MWh_{el}/y)	792	177	1,306	537
HP electrical energy requirement(MWh_{el}/y)	146	218	825	175
Total electricity requirement (MWh_{el}/y)	1,292	823	3,831	1,082
Waste heat production (MWh_{th}/y)	338	75	560	230
HP thermal energy production (MWh_{th}/y)	1,029	1,539	5,816	1,234

Table 8 represents that in the second scenario, a heat pump supplies the total heat demand of the plant. Therefore, electrical energy requirement of a heat pump is considered. Total electrical energy demand of plant is sourced by national electricity grid in this scenario.

Table 9. Energy balance of scenario 3 (heating and electricity needs covered, respectively, with gas from the grid and electricity from PV panels and grid)

Feedstocks	OFMSW	Livestock	WWS	Mixture
Mixing electricity requirement (MWh_{el}/y)	354	428	1,700	370
Upgrading electricity requirement (MWh_{el}/y)	792	177	1,306	537
PV electricity generation (MWh_{el}/y)	155	34	257	105
Number of solar panels	292	65	483	198
Total electricity requirement (MWh_{el}/y)	1,146	605	3,006	907
Waste heat production (MWh_{th}/y)	338	75	560	230
Gas boiler heat production (MWh_{th}/y)	1,029	1,539	5,816	1,234

In the third scenario, photovoltaic panels supply a portion of electrical energy requirement of the plant. Therefore, the number of required PV panels and total electricity generation by the photovoltaic system are calculated. The remaining electricity demand of the plant is sourced from the national electricity grid. As scenario one, the total heat demand of the plant is supplied by a gas boiler.

Table 10. Energy balance of scenario 4 (heating and electricity needs covered, respectively, with heat pump and electricity from the grid and PV panels)

Feedstocks	OFMSW	Livestock	WWS	Mixture
Mixing electricity requirement (MWh_{el}/y)	354	428	1,700	370
Upgrading electricity requirement (MWh_{el}/y)	792	177	1,306	537
HP electrical energy requirement(MWh_{el}/y)	146	218	825	175
PV electricity generation (MWh_{el}/y)	155	34	257	105
Number of solar panels	292	65	483	198
Total electrical requirement (MWh_{el}/y)	1,292	823	3,831	1,082
Waste heat production (MWh_{th}/y)	338	75	560	230
HP thermal energy production (MWh_{th}/y)	1,029	1,539	5,816	1,234

In the fourth scenario, both heat pump and photovoltaic panels are applied. The number of PV panels is the same as in scenario three. Additionally, heat pump's thermal energy production is the same as in scenario two.

Table 11. Energy balance of scenario 5 (heating and electricity needs covered, respectively, with heat pump and electricity from the CHP generation)

Feedstocks	OFMSW	Livestock	WWS	Mixture
Mixing electricity requirement (MWh_{el}/y)	354	428	1,700	370
Upgrading electricity requirement (MWh_{el}/y)	717	124	1,056	464
HP electrical energy requirement (MWh_{el}/y)	0	104	298	26
CHP electrical energy generation (MWh_{el}/y)	864	657	3,054	860
CHP electrical energy self-consumption (%)	79	100	100	100
Electrical requirement from grid (MWh_{el}/y)	223	0	0	0
HP thermal energy production (MWh_{th}/y)	0	738	2,100	188
CHP thermal energy production (MWh_{th}/y)	1,094	830	3,845	1,080
Waste heat production (MWh_{th}/y)	310	53	457	201
CHP thermal energy self-consumption (%)	100	52	64	85
Biogas percentage in CHP (%)	8.32	28.9	18.16	12.45

In scenario five, a portion of the produced biogas is burned in a CHP system. Therefore, the electricity generation and thermal energy production by the CHP is computed. Consequently, the biomethane production and waste heat production, as well as electrical energy requirement and thermal energy production of the heat pump are reduced. For livestock, wastewater sludge and mixture, the CHP system supplies the total required electrical energy of the plant, while for OFMSW, it covers just 82% of electricity demand. This results from an iterative process to determine the optimal performance condition of CHP system. If it is assumed that the CHP system supplies the total electricity demand of the plant for OFMSW, the CHP system will produce extra thermal energy relative to the heat energy demand of plant. To prevent overestimated thermal energy production, it is considered that the lack of electricity demand of plant is sourced from national electricity grid, just for OFMSW.

Table 12. Energy balance of scenario 6 (heating and electricity needs covered, respectively, with biogas boiler and electricity from the CHP generation)

Feedstocks	OFMSW	Livestock	WWS	Mixture
Mixing electricity requirement (MWh_{el}/y)	354	428	1,700	370
Upgrading electricity requirement (MWh_{el}/y)	715	131	1,077	466
CHP electrical energy generation (MWh_{el}/y)	846	560	2,780	835
CHP electrical energy self-consumption (%)	79	100	100	100
Electrical requirement from grid (MWh_{el}/y)	223	0	0	0
Biogas boiler thermal energy production (MWh_{th}/y)	0	856	2,435	219
CHP thermal energy production (MWh_{th}/y)	1,058	700	3,475	1,044
Waste heat production (MWh_{th}/y)	310	57	466	201
Thermal energy self-consumption by CHP	100	45	58	82
Biogas percentage in CHP (%)	8.32	24.63	16.53	12.09

In scenario six, the system is the same as in scenario five, except that the heating demand of plant is supplied by a biogas boiler and CHP, instead of the CHP system and a heat pump. consequently, electrical energy demand of plant is reduced, because heat pump does not exist.

In summary, the convenience of a scenario compared to others depends on several factors: the thermal and electrical energy demands of the feedstocks, depend on the physical-chemical characteristics of the feedstocks itself, the national gas grid and electricity costs. The results represent that OFMSW is an extremely productive feedstock, with a BMP of 75.6 Nm^3/y. It requires less thermal energy compared to the required electrical energy for a high amount of biogas upgrading process. Considering the livestock, the pig slurry has a lower BMP and constitutes the 86% of the feedstock, while the cattle manure has a higher BMP but accounts only for 14% of the feedstock. Livestock needs a high amount of thermal energy for the pre-heating of the substrates, however it has a low biogas production rate, resulting in a low electrical energy consumption for biogas upgrading stage.

4 Cost analysis

Considering plant life time of 20 years, the capital and operational costs for each scenario and feedstock are described (section 4.1). The revenue of selling biomethane associated with incentives are discussed in order to calculate net present value of plants (section 4.2). The internal rate of return that present the most efficient scenario and feedstock is represented (section 4.3).

4.1 Capital and operational costs

The listed scenarios represent six different solutions to supply thermal and electrical energy demands of plants. For each configuration, the Capital Expenditures (CapEx) include the CHP, construction and instalment of digesters, a heat pump, the upgrading system, the boiler and the PV plant costs. Also, the Operational Expenditures (OpEx) include the components maintenance and the electricity and heat costs from national grid, are computed for all scenarios and feedstocks. In this study, tariffs of 200 €/MWh$_{el}$ for electricity and 45 €/MWh$_{th}$ for natural gas heating are considered for the case study, Italy.

For each configuration, capital expenditures are computed depending on the scenarios. The capital and operational costs of upgrading plant is calculated according to:

$$Upgrading\ system\ CapEx\ (€) = \frac{C_{membrane} \cdot \dot{v}_{BG}}{h_{upgrading}} \qquad \text{Equation 8}$$

Where, C$_{membrane}$ represents the membrane cost (4800 €/m^3/h) based on reference values by TUW (50), $\dot{v}_{BG}$ produced biogas rate and h$_{upgrading}$ is the operating time of the biomethane upgrading system, which is assumed 8160 hours per year. The OpEx of upgrading system is considered as 2% of the CapEx itself (29,51).

$$Digester\ CapEx\ (€) = \frac{24\ (€)}{m^3\ (digester\ volume)} \qquad \text{Equation 9}$$

Where, average CapEx of each digester is equal 24€ per unit of digester volume. The OpEx of each digester is considered as 3% of the CapEx itself (29).

$$Heat\ pump\ CapEx\ (€) = \left(2982 \cdot {P_{th,HP}}^{0,6094}\right) \qquad \text{Equation 10}$$

Here, $P_{th,HP}$ represents the total thermal power of heat pump. The cost of heat pump includes the expenses of the required equipment and well digging. Also, operational cost of a heat pump is computed according to:

$$Heat\ pump\ OpEx\ (€) = (0.01 \cdot CapEx_{HP}) + (3 \cdot Q_{th,HP}) \qquad \text{Equation 11}$$

Where, $Q_{th,HP}$ represents heat demand of the plant after the recovery of waste heat production in the upgrading system.

$$PV\ CapEx\ (€) = C_{panel} \cdot num_{panels} \qquad \text{Equation 12}$$

Where, C_{panel} represents the photovoltaic panels costs (335€/panel) (52), and the num_{panels} indicates the number of required panels for different feedstocks. The photovoltaic panels system OpEx equal 10€ per unit of electrical power generated by the installed photovoltaic panels (53).

$$Boiler\ CapEx\ (€) = C_{boiler} \cdot P_{th,boiler} \qquad \text{Equation 13}$$

Where, C_{boiler} represents the boiler CapEx per unit of thermal power (270€/kW) (54), and $P_{th,boiler}$ is the thermal power of boiler. The boiler OpEx equals 17€ per unit of produced thermal power (kW) by a installed boiler (54).

$$CHP\ CapEx\ (€) = C_{CHP} \cdot P_{el,CHP} \qquad \text{Equation 14}$$

Where, the C_{CHP} represents the cogeneration plant CapEx per unit of generated electrical power (1800€/kW_{el}) (55) , and $P_{el,CHP}$ is the electrical power of CHP system. The CHP OpEx is equal to 10€ per unit of generated electrical power (kW) by the CHP system.

The yearly income also is represented by the incentivized selling price of the produced biomethane over plant life time of 20 years.

The following diagrams illustrate the CapEx and OpEx of various scenarios and feedstocks.

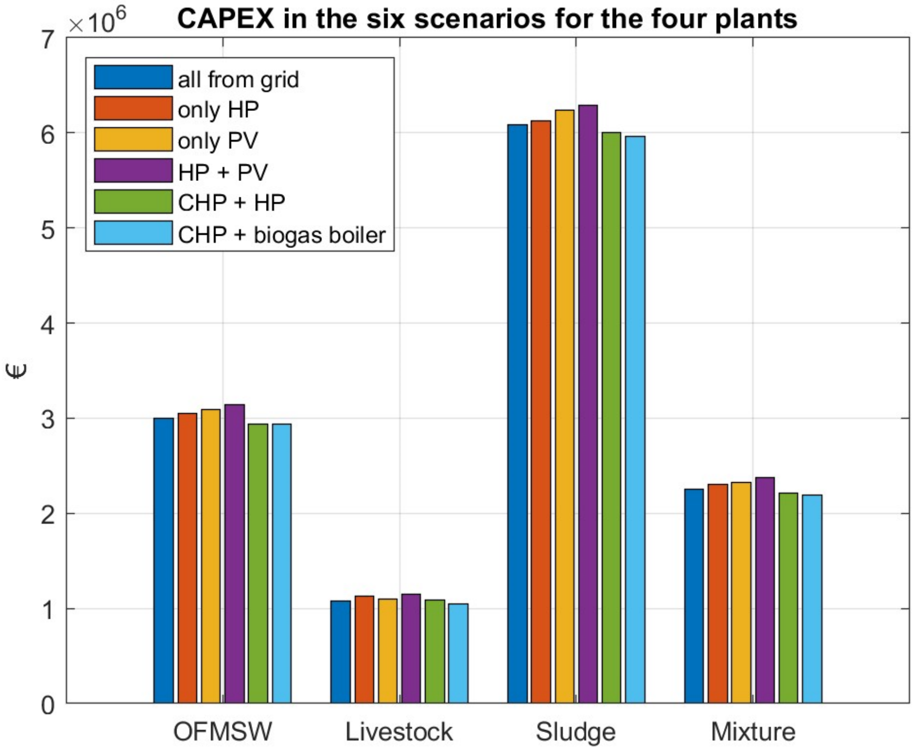

Figure 9. CapEx of six scenarios for different feedstocks

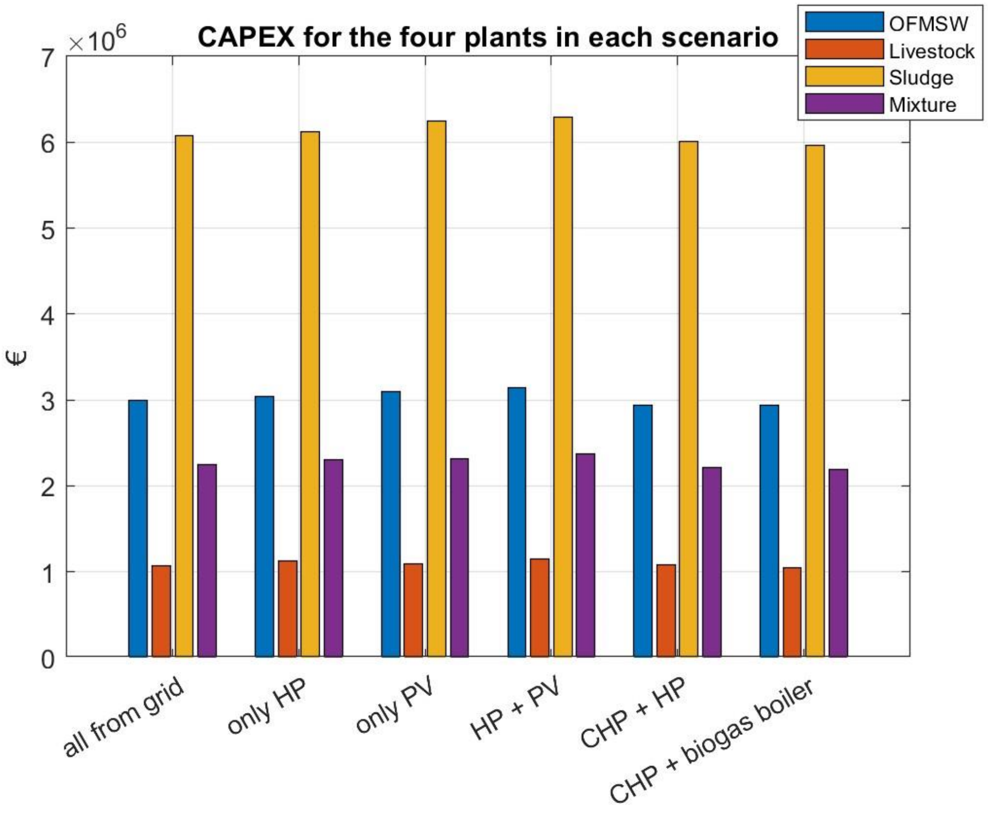

Figure 10. CapEx of different plants for each scenario

The wastewater sludge shows the highest CapEx among the mentioned feedstocks, due to the higher feeds to the plant, and then OFMSW, mixture and livestock, respectively. Furthermore, the highest CapEx is assigned to scenario four, this is associated with the use of a heat pump and photovoltaic panels across all feedstocks, simultaneously. Also, scenario six almost has the lowest CapEx across all feedstocks. This scenario involves a CHP system, which supplies plants electrical energy demand, while a biogas boiler supplies the required thermal energy of the plant.

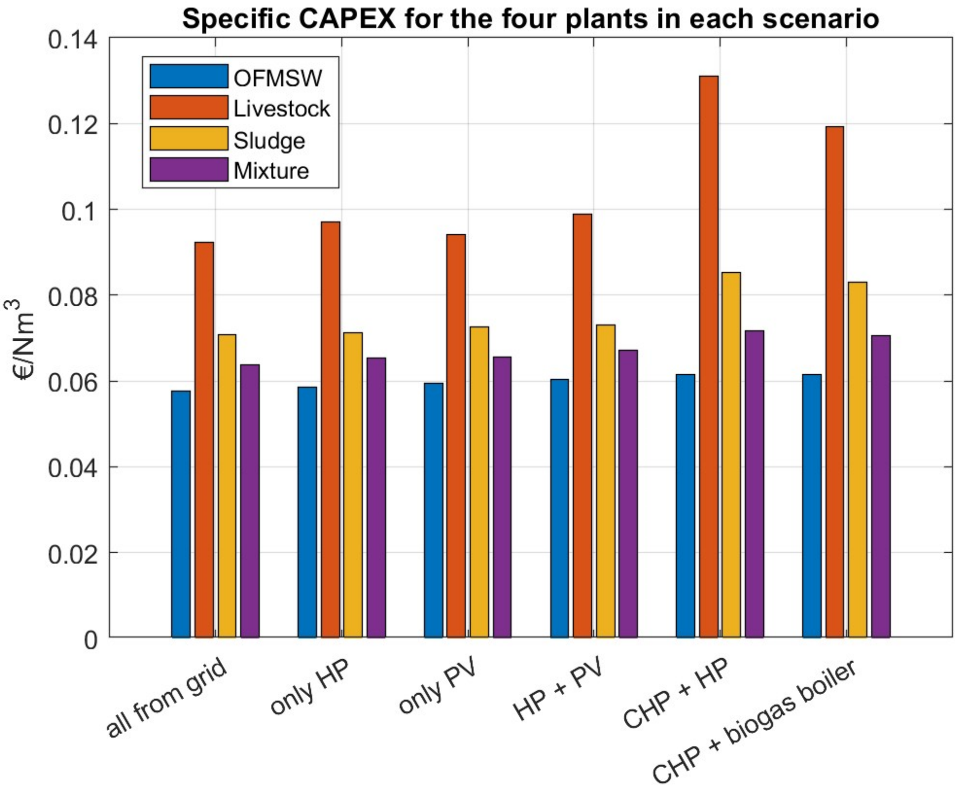

Figure 11. Specific CapEx of different plants for each scenario

This chart represents specific CapEx of different plants based on effective biomethane production rate. The diagram also illustrates that livestock feed, due to its composition including pig slurry with low BMP and cattle manure with high BMP, indicates the highest CapEx per unit of biomethane production rate. High thermal energy demand coupled with relatively low biogas production efficiency, contributes to the higher overall expenditures associated with this type of feedstock in all scenarios, specifically for scenario five.

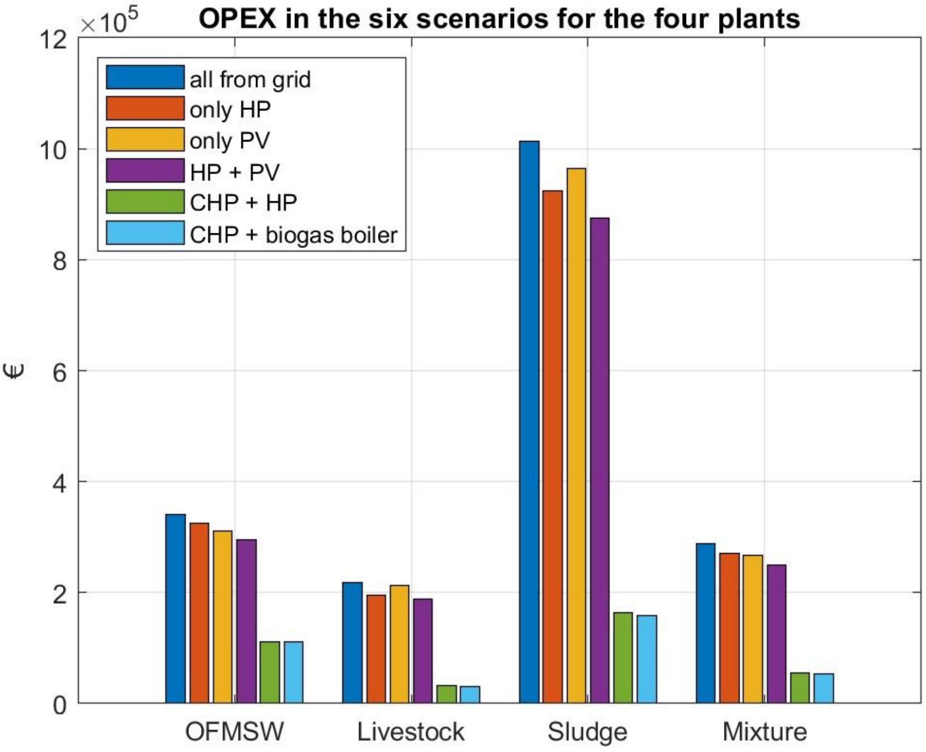

Figure 12. OpEx of six scenarios for different feedstocks

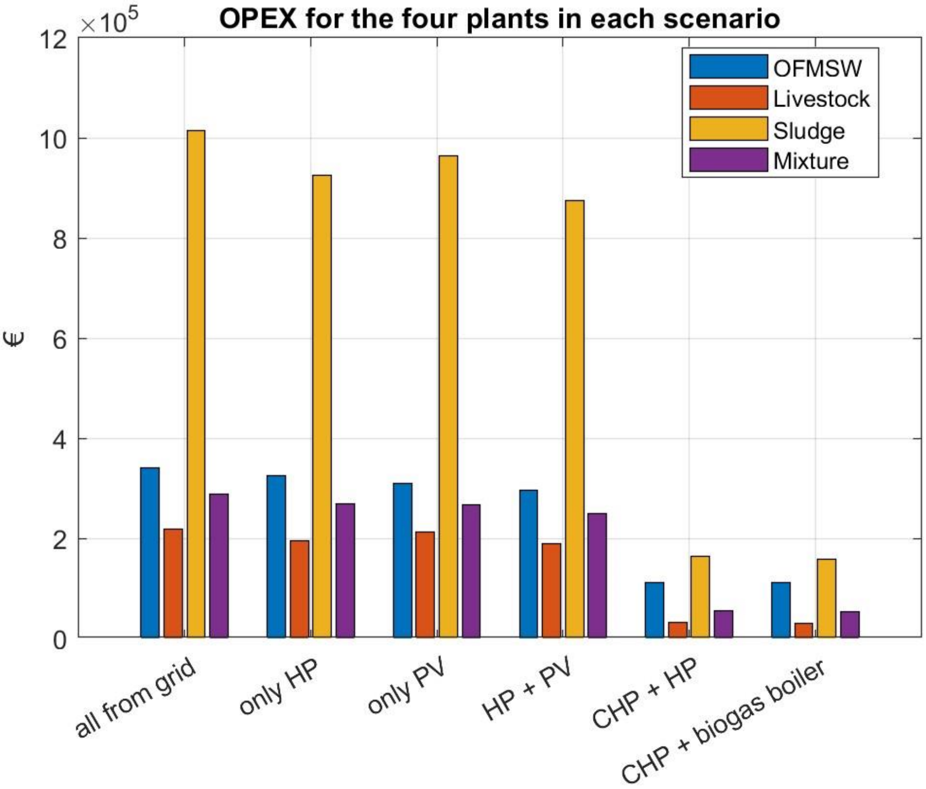

Figure 13. OpEx of different plants for each scenario

Diagrams represent operational expenditure of different scenarios across all feedstocks in a year. The scenario one illustrates the highest OpEx among all scenarios due to the high cost of electrical and thermal energy demand. In scenario three, photovoltaic panels contribute to supply a portion of the electrical energy demand of the plant, however the remaining electricity demand is supplied by the national electricity grid. This reliance on the grid leads to high OpEx. Using a heat pump to supply thermal energy demand, coupled with PV panels to meet a portion of electrical energy demand of the plant result in more independence from the national electricity grid. As a result, it achieves a lower OpEx compared to the other biomethane production plants.

Scenarios five and six are approximately the same in terms of OpEx. Also, for the OFMSW in scenario five and six, there is no need for a heat pump and a biogas boiler and consequently, there is no expenditure (OpEx and CapEx) associated with these components for this feedstock.

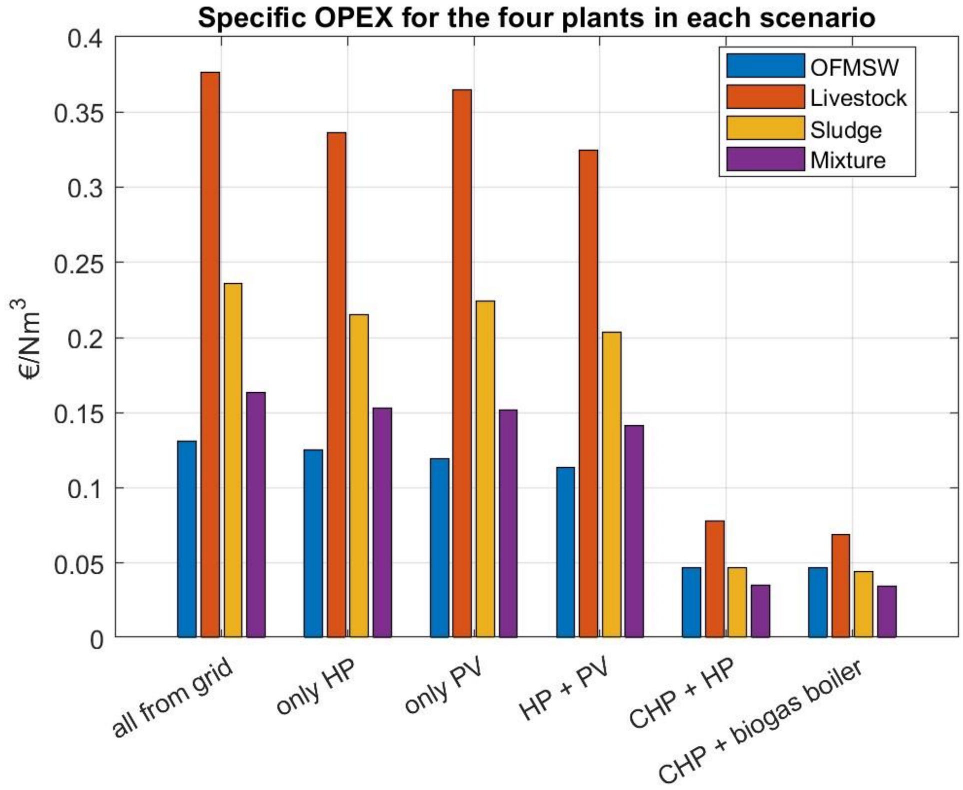

Figure 14. Specific OpEx of different plants for each scenario

This diagram represents specific OpEx of different plants based on effective biomethane production rate. The chart also illustrates that the livestock feed results in the highest specific OpEx for fully biomethane production plants. The highest amount is assigned to scenario one, where all the energy demand of plant is supplied by national grid. The results notice that the importance of alternative energy sources and strategies to optimize the OpEx for biomethane production plants.

Employing the CHP system coupled with a heat pump illustrates the higher specific OpEx compared to the CHP system in conjunction with a biogas boiler. This is attributed to the fact that applying a heat pump requires electrical energy and consequently, it leads to increment of electricity demand of plant. To meet the additional electricity demand caused by a heat pump, a higher percentage of biogas should be directed to the CHP system to generate electricity demand of the plant.

4.2 Revenue

The source of yearly revenues is the incentivized feed in tariff, with a specific rate of 0.70 €/Nm^3 of biomethane production (29). This tariff includes both the sale price of the biomethane as well as incentives provided for injecting biomethane into the national grid.

Net present value of the plant is also computed according to:

$$NPV\ (€) = -CapEx + \ (yearly\ profit\ \cdot\ plant's\ life\ time) \qquad \text{Equation 15}$$

Equation 15 represents the NPV after the plant life time.

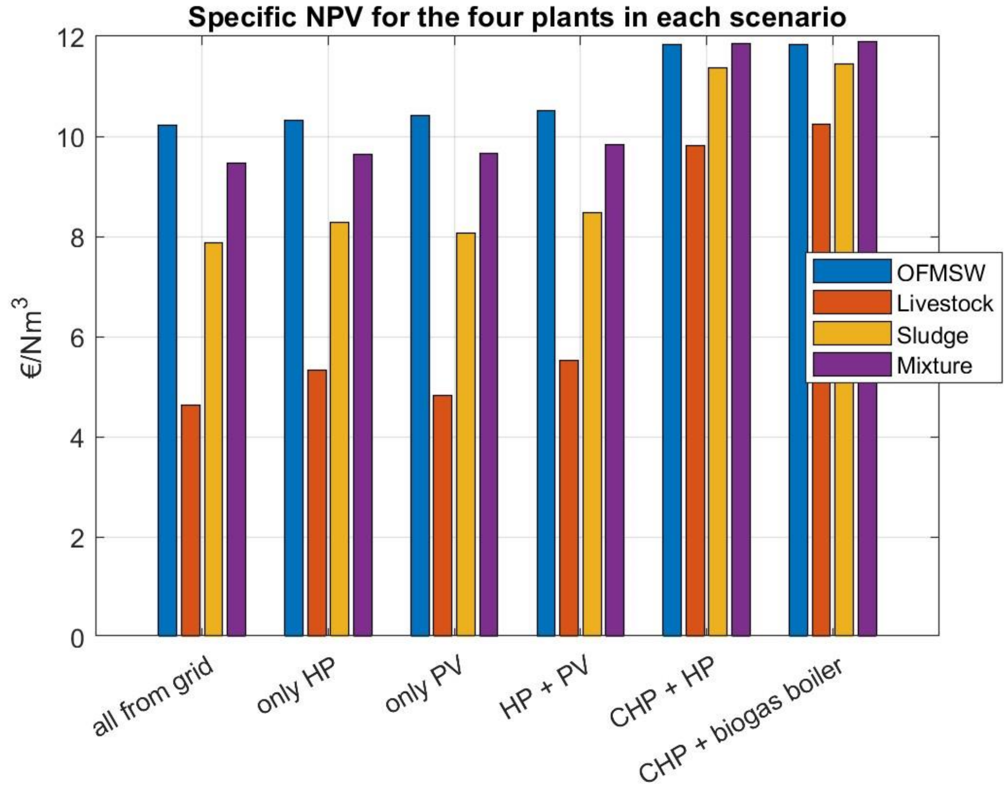

Figure 15. Specific NPV of different plants for each scenario

The chart represents specific NPV of the different plants based on effective biomethane production rate. The diagram also illustrates that the employing the CHP with a heat pump or a biogas boiler result in the highest specific NPV. The OFMSW also indicates a higher specific NPV for fully biomethane production plants due to it has a high BMP compared to the other feedstocks, which results in the higher revenue from selling biomethane.

4.3 Results of the economic analysis

The CapEx, OpEx and revenues are calculated for each configuration over the plant life time. Also, the yearly profits are calculated according to the differences between yearly revenue derives from selling biomethane and OpEx of the plant.

The profitability of investment is computed using the following equation, which represents the Net Present Value (NPV) of zero.

$$NPV = 0 = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n} \qquad \text{Equation 16}$$

The variable $n\ (y)$ is the plant life time and $CF_n\left(\frac{€}{y}\right)$ represents the annual cash flows for a plant. This is equal to the difference between the yearly profit for n>1 and the capital expenditures for n=0. Also the internal rate of return (IRR) is considered that represents the convenience of the investment. Higher IRR values are considered more effective as they indicate a greater rate of return and a more attractive investment opportunity.

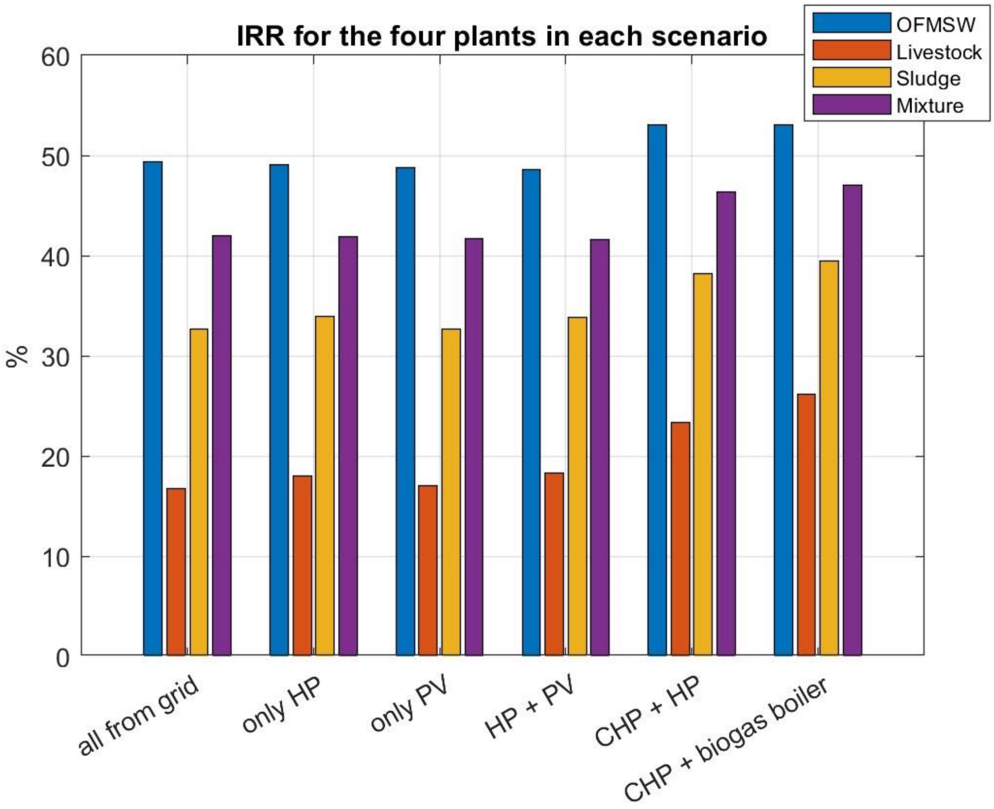

Figure 16. The plants internal rate of return in Italy

The diagram provides the internal rate of return (IRR) for different scenarios related to different feedstocks. This gives opportunity to determine the most effective scenarios.

The bar chart also indicates that the highest IRR is related to scenarios six and five, which involves a combination of CHP system and a biogas boiler, or a combination of CHP system and a heat pump.

For scenarios one to four, fully biomethane production plants, the highest IRR is related to employing only a heat pump, and both a heat pump and PV panels system to supply energy demand of the plants. This is because employing a heat pump to supply thermal energy demand of plant will result in less dependency on national grid.

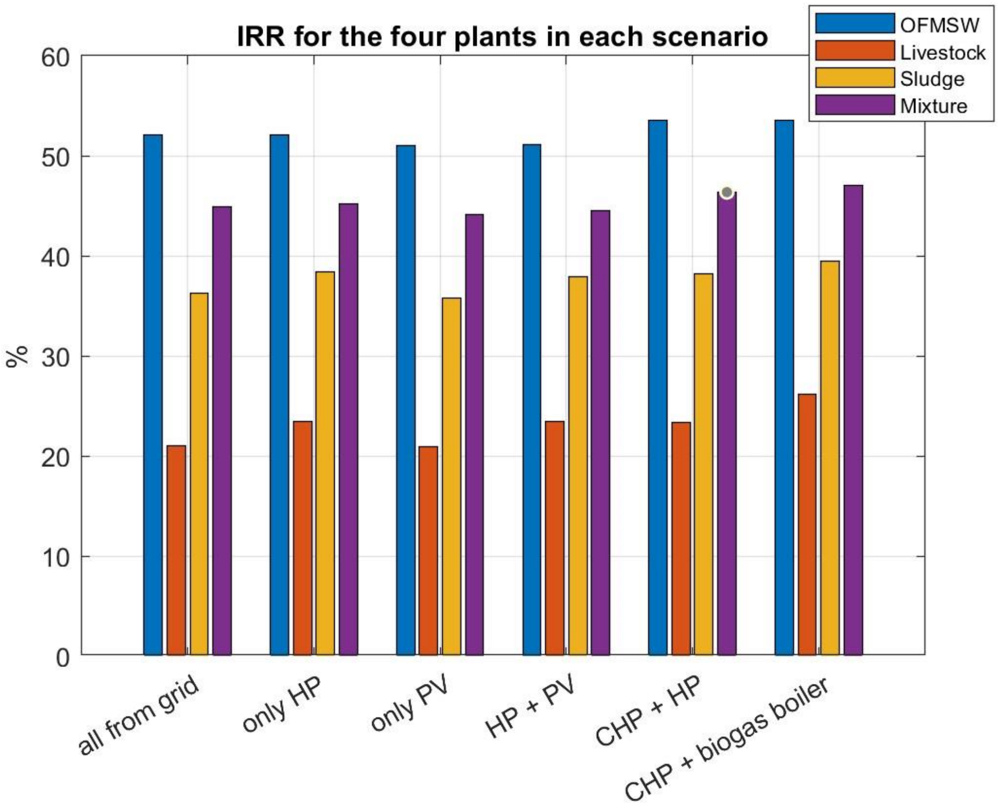

Figure 17. The plants internal rate of return in France

Another configuration is conducted based on an electricity price of 130€/MWh$_{el}$, the typical electricity price in France. The results are almost similar for scenarios five and six. However , in the case of fully biomethane production plants, the generated IRR is higher compared to the case study, Italy. The highest IRR is also related to the employing only a heat pump to supply thermal energy demand of plant. On the other hand, employing only PV system or a heat pump and PV panels system to supply electricity demand of plant are not recommended due to the low typical price of electricity in France.

It is important to note that the IRR is not the only factor to determine the most sustainable scenarios. Other factors also should be considered such as environmental impacts, feedstocks availability, plant location, energy price, social acceptance and etc to determine most effective scenarios.

5 Conclusions

This study investigates the environmental benefits of employing a geothermal and solar energy sources to supply the energy demand of fully biomethane production plants and the combination of biomethane production and the CHP generation plants to achieve the 2050 EU decarbonization targets. The open-loop geothermal system and SPR-MAX3-400 photovoltaic panels are applied to meet the required thermal and electrical energy demand of biomethane production plants. The techno-economic assessments indicates that the most sustainable technology is associated to the employing a heat pump to supply thermal energy demands, and photovoltaic panel systems to meet the electrical energy demands of fully biomethane production plants for a typical electricity price in Italy. However, employing PV panels system is not recommended for plants with a typical electricity price in France.

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List of abbreviations and symbols

AD	Anaerobic digester (or digestion)
BM	Biomethane
CHP	Combined heat and power
PV	Photovoltaic
EU	European Union
GHG	Greenhouse gas
COP	Coefficient of performance
NPV	Net Present Value
BMP	Biomethane productivity
OFMSW	Organic Fraction of Municipal Solid Waste
CapEx	Capital Expenditures
OpEx	Operational Expenditures
WWS	Waste Water Sludge
HP	Heat pump