UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA CIVILE, EDILE E AMBIENTALE
Department Of Civil, Environmental and Architectural Engineering

Corso di Laurea Magistrale in Environmental Engineering

TESI DI LAUREA

Energy assessment of a biogas plant in northern Italy

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ANNO ACCADEMICO 2021-2022

Abstract

In a historical period like the current one, in which the increasing need to mitigate climate change meets an energy price that is growing dramatically, it becomes of fundamental importance to monitor and continuously improve energy performance to overcome the economic crisis.

The objective of the work carried out is to provide the company Società Estense Servizi Aziendali S.p.A. (hereinafter S.E.S.A.) with an assessment on the energy use in the period from January to August. The objective is to establish if company operating conditions are energetically optimized or not.

To do this, the company's processes, consumption and production, operating conditions and technical characteristics of the plant, existing contracts and all the boundary conditions that can affect the result of the analysis were analyzed. A representative energy profile was then built and, starting from data collected, the optimal scenario for each month was established and compared with the real situation of the same month.

What emerged, finally, is that the company is moving in the right direction, a result that now, thanks to the analysis, is numerically demonstrable.

After the assessment, a forecasting model was developed to improve company energy performance.

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1. Introduction

At the base of the study presented below there is the analysis of three different energy carriers, such as electricity, methane and biogas from the treatment of biowaste (kitchen waste), correlated with the different uses of biogas that the company can carry out, namely production of electricity for self-consumption, production of electricity for sale and production of biomethane.

The reasons why I decided to carry out this type of analysis are mainly two. Firstly, the energy crisis that Europe is going through in this historical period and the increasingly felt problem of climate change. Secondly, the possibility of being able to make a practical contribution to a leading company in waste treatment, able to transform a waste product such as the biowaste fraction of separate waste collection into a precious energy resource.

The objective of this thesis is to carry out an energy assessment to determine what are the optimal operating conditions for a plant that has undergone numerous changes over the years and that is facing a historical period in which the price of electricity and methane has soared. The plant has been extensively developed and significant upgrades have been implemented compared to what it was originally; therefore, such an energy analysis is necessary to provide quantifiable results.

To do this, a detailed on-site analysis was conducted, working closely with the staff and analyzing in detail the operation of the plant, technical data of production and consumption, active contracts, bills and plant limits. After that, the real operating conditions of each month from January to August were reconstructed; all the alternative operating conditions were developed and compared with real situations to understand if the company can do better or not.

Thanks to the analysis conducted, it was possible to determine interesting results that will be exposed in the conclusion of this thesis.

2. Circular Economy and legislation

The Ellen MacArthur Foundation provided the most well-known description of the circular economy, defining it as “an industrial economy that is restorative or regenerative by intention and design.” In a similar vein, Geng and Doberstein, focused on the Circular Economy's application in China, define it as the “realization of a closed loop material flow in the entire economic system.” A circular economy, according to Webster, is one that “seeks to maintain products, components, and materials at their highest utility and worth, at all times.” Accordingly, Yuan et al. state that “the core of the Circular Economy is the circular (closed) flow of materials and the use of raw materials and energy through multiple phases.” According to Bocken et al., the Circular Economy is defined as “design and business model strategies that are slowing, closing, and narrowing resource loops.”

Based on these different contributions, Geissdoerfer et al. define the Circular Economy as “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling”. (Geissdoerfer et al., 2017)

Figure 1: representation of Circular Economy's concept.

S.E.S.A. is a company that over the years has developed an extremely effective energy and environmental monitoring system, able not only to adequately treat a large amount and variety of waste, but to do so under a circular economy perspective, trying to go as far as possible in this direction.

In fact, until 2018, the year in which it decided to upgrade by installing the biogas treatment line to produce biomethane and CO_2, all the biogas produced from the treatment of biowaste was used within the company's cogeneration groups to produce electricity for its livelihood and recovering the heat generated to exploit it through a district heating network, connected to with more than 100 users. In addition, heat recovery allows the company to maintain an appropriate biodigester temperature, thus obtaining an anaerobic digestion process that is always optimized and, above all, allowing considerable savings in electricity consumption, with a consequent reduction in pollutant emissions into the atmosphere. In addition, part of the digestate produced by the biodigesters is mixed with green waste to produce compost and, another share, is purified by means of an internal wastewater treatment plant. Doing that, all possible water is recovered, water that is used for washing equipment and areas of the site, or in case of emergency. In 2018, the company started up a biogas treatment plant to produce biomethane and CO_2. Part of the biomethane produced is used internally to power vehicles.

Not only that, but the company has also always aimed to optimize all the processes/machinery/devices present. Therefore, even in methane-powered engines that the company use to produce electricity for self-consumption, thermal energy is recovered, significantly increasing their efficiency. For S.E.S.A. environmental sustainability has always been a key point.

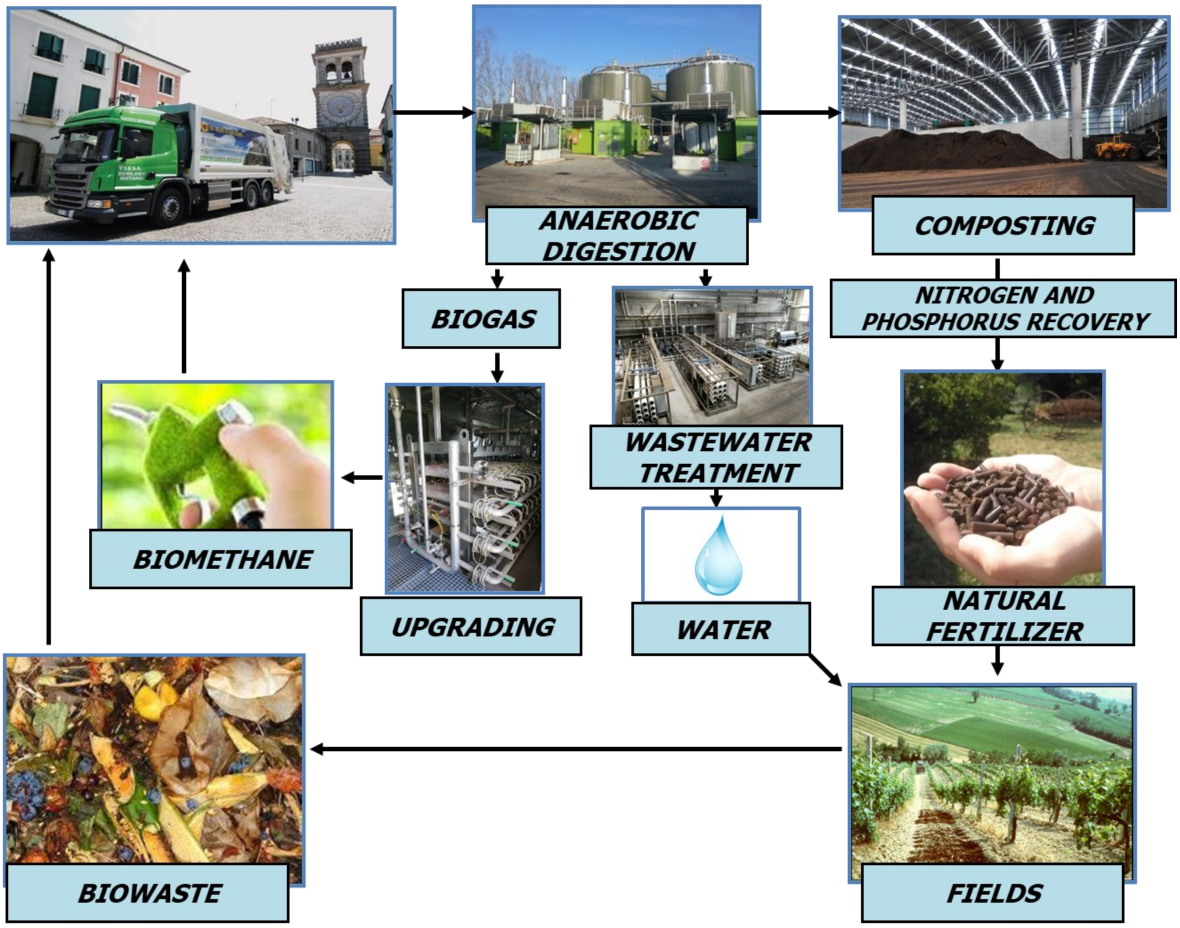

Figure 2: S.E.S.A. circularity scheme.

From 2015 the company periodically carries out balance sheets and energy analysis. Since 2018, following the installation of the biomethane and CO_2 production line, the need for electricity and atmospheric emissions quantified in TOE have increased: once the threshold of 10.000 TOE/year has been exceeded, as required by law, the need arose for the appointment of an energy manager, capable of monitoring and managing the company's energy consumption in the best possible way. (Il portale FIRE dedicato agli Energy Manager e agli EGE, 2022)

2.1. *The role of the energy manager*

An energy manager, as the term suggests, is a subject who has the task of managing what concerns energy within a company, a public body, or more generally a structure, verifying consumption, optimizing them and promoting interventions aimed at energy efficiency and the use of renewable sources.

The energy manager, therefore, verifies consumption, through ad hoc audits or, if available, through the reports produced by remote management, remote control and automation systems. It is therefore concerned with optimizing consumption through the correct regulation of the systems and their appropriate use from an energy point of view, to promote energy-conscious behavior on the part of employees and/or occupants of the structure and to propose improvement investments, possibly able to improve production processes or the performance of related services.

Another function that often concerns the energy manager is that of purchases of electricity and other energy carriers. Clearly in this case it is a matter of reducing purchase costs, possibly promoting the correct management of electrical loads to avoid power peaks that involve higher costs.

Among the less common but useful options there is the possibility of collaborating with the purchasing department to promote procedures that promote the so-called green procurement and the purchase of machinery characterized by low energy consumption and therefore low operating costs. (Il portale FIRE dedicato agli Energy Manager e agli EGE, 2022)

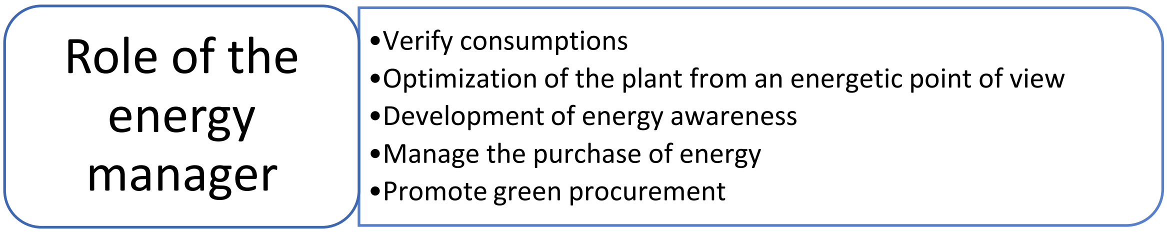

Figure 3: the role of the energy manager.

To support the role played by the energy manager, the UNI CEI EN ISO 50001 standard is available.

2.2. UNI CEI EN ISO 50001

ISO 50001 *("Energy Management Systems - Requirements and Guidelines for Use")* offers organizations in any sector, both private and public, management strategies that aim to bring:

- an increase in energy efficiency;
- cost reduction;
- an improvement in energy performance, which must therefore be integrated into the management of the daily activities of the organization.

The objective of ISO 50001 is in fact to allow organizations to create and maintain an Energy Management System (EMS) that allows them to continuously improve their energy performance.

Key points

ISO 50001 specifies the requirements that an energy management system must have, enabling an organization to have a systematic approach for continuous improvement of its energy performance, also considering legal obligations. The standard, therefore, defines the requirements applicable to the use and consumption of energy, including the activity of:

- measurement
- documentation
- design
- purchase for equipment
- as well as the processes and personnel that contribute to determining energy performance.

The standard does not establish specific energy performance criteria. It is a voluntary adhesion standard, supported in national and European legislation.

The standard allows the organization to achieve several advantages:

- gain knowledge of energy consumption internally;
- monitor and reduce (being able to objectively quantify the reduction efforts) its energy needs;
- assess compliance with legislative constraints and thus be able to give public feedback;
- be able to demonstrate more easily compliance with the obligations to which the organization is subject;
- it is useful to credibly develop one's environmental reputation. (Comitato Tecnico ISO/TC 301 Energy management and energy savings, 2018)

The main objective of the analysis conducted in the following chapters is to use the results obtained as a starting point to develop a system of continuous improvement of energy consumption and production, and to allow the company, once the objectives defined by the standard have been achieved, to obtain the certification UNI CEI EN ISO 50001.

3. Description of the site and activities carried out

Società Estense Servizi Ambientali (hereinafter S.E.S.A.) is a company in northern Italy, located in Este (PD) and specialized in the collection and treatment of recoverable fractions of separate urban collection. The total area of the site is over 500.000 m^2. Below are the activities carried out.

Figure 4: view of S.E.S.A. of site.

3.1. Collection and transport of municipal and special waste

S.E.S.A. carries out collection and transport of municipal solid waste, differentiated into: biowaste, paper and cardboard, glass, plastic and cans, dry waste, bulky waste, inert waste, food oils, waste from green maintenance. Separate waste collection has assumed a priority role: on one hand it allows to reduce the quantity of waste to be sent for disposal in landfills, and on the other it positively affects the entire waste management system, allowing its processing and ensuring the correct recovery of materials in raw materials and energy. The service is also applied to the collection and transport of non-hazardous special waste, by renting or selling containers for collection and transport to the plant. The transport of hazardous municipal waste, i.e. expired medicines, spent batteries and toxic or flammable waste, is also carried out to a small extent.

3.2. Selection and storage of differentiated and undifferentiated dry waste

The incoming separated and undifferentiated dry waste is processed in a modern plant that operates an automatic selection using optical sensor and, in part, manual sorting in order to obtain End of Waste (paper, cardboard, tetrapack) and waste destined for recovery at other authorized plants (plastic, wood, glass, metals and other mixed materials). The plant is allowed to treat up to 98.000 tons/year.

3.3. Landfill management for non-hazardous waste (with priority for municipal waste)

The plant, built according to provincial provisions, is managed directly by S.E.S.A. and has been classified as a landfill for non-hazardous waste at the service of urban collection. The waste to be delivered, consisting of materials that can no longer be processed or recycled, is weighed and recorded. After verification of its compliance with acceptance, which takes place in predetermined areas, it is handled and processed during the day, by compaction. At the end of the day, the waste advance front is covered. Thanks to the success of separate waste collection organized in the municipalities belonging to the catchment area, the amount of waste delivered has been decreasing over time. Since 1995, the interventions and works carried out have been manifold and have concerned the greening of the site by planting in the areas surrounding the plants, the formation and grassing of the landfill slopes and the leachate conveyance network, as well as the creation and strengthening of the biogas collection network. Today, the use of the landfill is residual when compared with the recovery activity carried out in the other plants, in fact it is authorized for the disposal of a maximum of 35.000 tons/year.

Figure 5: S.E.S.A. landfill.

3.4. Internal laboratory management

The laboratory carries out chemical, chemical-physical, microbiological and commodity analysis of urban, industrial and agricultural waste, soil improvers, soils, as well as air and environmental pollution control analysis. The accreditation according to the 17025 standard certifies the technical competence of the personnel to carry out specific tests, its impartiality, the use of adequate instrumentation, in general the compliance with the technical and management requirements of the sector. The laboratory was created mainly to assist the management of the production processes of the plants, through periodic checks of the treated materials that allow the optimization of these processes and the development of the plant. At the same time, particular attention is paid to the study of the main chemical-physical and biological parameters of the compost, with the aim of obtaining an increasingly high quality of the final product.

3.5. The composting plant and anaerobic digestion

The treatment of biowaste coming from separate collection (kitchen waste, green waste, etc.) is the main activity of the company and involves the production of organic soil improvers for agriculture, energy recovery with the production of electricity to be fed into the distribution network, the production of thermal energy for the internal and urban district heating network and the production of biomethane and CO_2 from biogas.

The objective of the production process is to enhance the incoming putrescible waste through various processes that allow its recovery in the form of compost and energy.

The composting process consists of the controlled transformation and stabilization of biowaste. After arrival at the plant, weighing and controls on incoming waste, materials are delivered to the biowaste treatment plant and pre-treated before being sent for biodigestion or composting.

The pre-treatment process consists of the following steps:

1. Laceration of bags by shredder/bag opener (biowaste must be contained in appropriate bags/shoppers that are opened for subsequent screening);
2. Screening with removal of foreign bodies (consisting mainly of plastic bags / shoppers);
3. At the end of the process a product consisting of pumpable biowaste is obtained.

One fraction of this product is then mixed according to defined proportions (70% biowaste and 30% structuring material) and subjected to controlled bioxidation and sanitation between 45 and 70 ° C for at least 16 days, in order to accelerate the natural degradation processes and sanitize the material. The bioxidized material is then matured in static cells with controlled aeration and after at least 45 days is refined and subjected to analytical control. The whole process is automatically managed by a computerized control system that continuously corrects the air flows and conditions concerning the composting facilities and plants. At the end of the composting process, soil improvers are obtained in compliance with Legislative Decree 75/2010 (certified by Consorzio Italiano Compostatori as well) and valuable for gardening.

The second fraction, instead, is pumped into 10 anaerobic biodigesters with which the company is equipped. The material is loaded from above inside each of them. It is kept at a temperature of about 52 °C to optimize the digestion process of thermophilic bacteria. Biogas is obtained as a product of the digestion process, which can be used for different purposes: production of electricity and heat from cogeneration and production of biomethane and CO_2. Generally one ton of biowaste generates 150 Sm^3 of biogas. Downstream of the digestion process there is also the production of a liquid fraction called digestate, which is extracted from digesters and sent to the company's internal wastewater treatment plant or to the composting plant.

Figure 6: anaerobic biodigestors.

The quality of biogas can vary during the year: it depends strictly on the quality of the biowaste entering the biodigesters, a quality that varies mainly with the variation of people's diet with the change of seasons during the year. In the last year, after the analysis carried out, an average composition of biogas can be considered as follows: 63 - 68% methane, 31 - 36% CO_2 and 1% other gases.

3.6. Electricity production

The peculiarity of S.E.S.A. lies in the ability to produce energy from waste without subjecting it to combustion. Part of the biogas produced by biodigesters is in fact used to power electricity and heat production plants. The biogas, consisting of methane, carbon dioxide and other gases in smaller quantities is compressed, purified and finally sent to cogeneration stations for the production of electricity and heat.

The company is equipped with n. 9 cogeneration plants powered by biogas from waste, n. 1 cogeneration plant powered by biogas from agricultural biomass, n. 2 cogeneration plants powered by fossil methane.

An amount of biogas is constantly sucked into the collection network present in the landfill, through a suction system that constantly keeps the landfill in depression, avoiding the escape of gas. The aspirated biogas is sent to a cogenerator, identified as SESA 3, with a nominal power of about 1,41 MW of electricity. The electricity produced by the cogeneration plant is self-consumed, and the heat is currently exploited both in company infrastructures and through an urban district heating distribution network serving various public users in neighboring municipalities (including the Este hospital) whose use allows both energy savings of fossil fuels and less pollution, due to the decommissioning of old heating plants, in favor of district heating.

Also, inside the site there is another anaerobic biodigester, which, however, unlike the previous ones, is not fed by biowaste coming from collection, but by agricultural biomass. The principle of operation is the same as the digesters seen above and biogas produced is used to run a biogas cogenerator, identified as BIO 5.

Cogenerators are divided into two sections as they have two different roles:

- The first cogeneration section consists of SESA 1, SESA 2, SESA 4 and SESA 5 cogenerators. The electricity produced by these cogenerators is used within the S.E.S.A. site to meet the company's energy needs.
- The second cogeneration section consists of BIO 1, BIO 2, BIO 3, BIO 4 cogenerators. The electricity produced by these cogenerators is sold and cannot be used internally by the company. Each plant is equipped with a connection cabin and a meter connected to the distribution network, to which the electricity produced is supplied.

The table below shows the power generated by each cogeneration group.

Table 1: First cogeneration section and electric power generated by each cogenerator.

I cogeneration section	Electric power kW
SESA 1	1064 kW
SESA 2	1416 kW
SESA 4	1415 kW
SESA 5	1415 kW

Table 2: second cogeneration section and electric power generated by each cogenerator.

II cogeneration section	Electric power kW
BIO 1	998 kW
BIO 2	998 kW
BIO 3	998 kW
BIO 4	998 kW

The company also has another biogas cogenerator, called BIO 6, with an electric power of 1067 kW, used only in case of failure of one of the SESA engines.

In the analysis, since cogenerator SESA 3 and BIO 6 has the same role of the cogeneration section I, we considered them part of the I cogeneration section; regarding BIO 5, its role is the same of the other BIO engines, and also the incentive. It is not considered part of the II cogeneration section because its feeding comes from agricultural biomass and not from biowaste from separate collection.

3.7. Biomethane and CO_2 production lines

In 2018 the company decided to make another major upgrade and start treating biogas to produce biomethane.

Part of the biogas produced inside the biodigesters is transported by pipelines to the biogas treatment plant for the purification of the latter, obtaining biomethane and food-grade CO_2 as final products.

In this section of the site there are n. 4 biogas treatment lines, capable of producing a maximum of 5000 Sm^3/h of biomethane in total. The biomethane produced then follows several paths: a part of it is used to power the company's vehicle fleet, another small part is sold through an intermediary to companies in partnership with SESA and that collaborate with it in waste treatment (about 500 vehicles in total), and all the remaining quantity is introduced and sold through the SNAM network, the main

European operator in the transport and storage of natural gas, with an infrastructure capable of enabling the energy transition. (SNAM, 2022)

Downstream of the treatment, CO_2 is also obtained as a second product with a degree of purity above 99%, which is recovered, liquefied, stored and analyzed. This is sold as food grade CO_2 and used in the production of sparkling drinks. Since CO_2 is obtained as second product of the biogas treatment line to produce biomethane, the quantity produced is directly related to the amount of biomethane produced.

3.8. Methane engines

The maximum electrical power that can be taken from the grid by the company can reach a maximum of 6500 kW, after which the system goes into protection, causing a blackout. For this reason, the company, being energy-intensive, has also equipped itself with two engines powered by fossil methane to produce electricity and heat in order to meet any requests for surplus energy.

The first engine installed, hereinafter identified as ECOMAX or TLR1, is capable of generating an electrical power of 3000 kW; the second engine, installed in the summer of this year and hereinafter identified as TLR2, is capable of generating an electrical power of 4500 kW.

3.9. Photovoltaic

The production of energy from renewable sources is further integrated by the exploitation of the installed park of photovoltaic panels.

Within the site there are:

- n. 1 photovoltaic plant of 50 kW for self-consumption of electricity;
- n. 1 photovoltaic plant of 282 kW for self-consumption and supply of electricity;
- n. 1 photovoltaic plant of 993 kW for the supply of electricity;
- n. 1 photovoltaic plant of 994 kW for the supply of electricity

for a total of 2.3 MW. Since the amount of energy sold from the 282 kW photovoltaic plant is very small, in the analysis we assumed that all the electricity generated by this plant is used for self-consumption.

Table 3: summary of engines and PV systems present in the site.

Plant/engine	Power	Utilization	Feeding
I cogeneration section	5310 kW	Self-consumption	Biogas from biowaste
II cogeneration section	3992 kW	Cession	Biogas from biowaste
SESA 3	1416 kW	Self-consumption	Biogas from landfill
BIO 5	999 kW	Cession	Biogas from agricultural biomass
TLR1 (ECOMAX) engine	3000 kW	Self-consumption	Fossil methane
TLR2 engine	4500 kW	Self-consumption	Fossil methane
Photovoltaic 50 kW	50 kW	Self-consumption	Sunlight
Photovoltaic 282 kW	282 kW	Self-consumption/cession	Sunlight
Photovoltaic 993 kW	993 kW	Cession	Sunlight
Photovoltaic 994 kW	994 kW	Cession	Sunlight

4. Data collection

The data collection was a very complex and time-consuming job. It was done using different research methods, combining and comparing them with each other:

- analysis of the company's internal production registers with regard to the production of biogas, biomethane and CO_2;
- use of the Energy Sentinel software: the company is mapped and monitored continuously through the use of this software that allows you to identify in real time the power generated and consumed by all electrical utilities connected with it (more than 110 points). Also historical data are available. With this software it was possible to monitor the average power consumed daily by the company, the power generated by photovoltaic systems, biogas engines and methane engines and, consequently, the electricity produced by each plant;
- analysis of electricity and methane bills to compare and verify the correctness of the monitoring carried out with Energy Sentinel, as well as to identify the costs of electricity and methane purchased;
- analysis of the data provided by Enel Distribuzione regarding the electricity sold to verify the accuracy of the data obtained with Energy Sentinel, as well as to identify the gain obtained from the sale of electricity;
- analysis of invoices issued for the sale of biomethane and CO_2 and comparison with internal production data, as well as to identify the gain obtained from the sale of biomethane and CO_2.

Of fundamental importance was the comparison of each data with multiple sources to verify its correctness and truthfulness.

Before proceeding, it is necessary to define the two parameters on which the prices of electricity and methane are based: PUN and PSV.

- the PUN (in italian: Prezzo Unico Nazionale) is the wholesale reference price of electricity that is purchased on the Italian Power Exchange (IPEX). It represents, therefore, the national weighted average of the zonal electricity sales prices for each hour and for each day. (Enel Energia, 2022)
- the virtual exchange point PSV (in italian: Punto di Scambio Virtuale) is the main meeting point between supply and demand of the gas market in Italy. Here the wholesale gas price is defined and based on this value, gas suppliers evaluate the price of the gas raw material to be applied to end customers. The difference between the two prices is closer to the unit revenue of the suppliers. (Luce – Gas, 2022)

The following tables show the data collected necessary for the analysis from the beginning of the year until August, i.e. the energetic profile of each month.

Table 4: energy profile from January to March.

YEAR 2022			Jan-22	Feb-22	Mar-22
Methane price	PSV	€/MWh	86,909	82,832	128,317
		€/Sm^3	0,951	0,907	1,404
		cost CH_4/PSV CH_4	1,085	1,068	1,028
Electricity price	PUN	€/MWh	224,500	211,690	308,070
		cost E.E./PUN E.E.	1,324	1,265	1,125
Purchased methane	Quantity	Sm^3	556.305	512.048	477.910
	Total cost	€	574.271 €	495.569 €	689.643 €
	Price for Sm^3	€/Sm^3	1,032	0,968	1,443
Purchased electricity	Quantity	kWh	586.126	1.095.730	1.441.895
	Total cost	€	174.220 €	293.510 €	499.762 €
	Price for kWh	€/kWh	0,297	0,268	0,347
Biogas engine production	Electric energy production SESA 1-2-4-5-3	kWh	2.483.150	1.919.986	1.530.263
	Electric energy production BIO 6	kWh	139.107	160.598	580.344
	Biogas used	Sm^3	1.170.241	928.507	941.905
	Electric energy production BIO 1-2-3-4	kWh	2.759.290	2.513.511	1.935.559

	Biogas used	Sm^3	1.537.265	1.400.051	893.439
	Electric energy production BIO 5	kWh	685.389	623.701	66.444
Methane engine production (ECOMAX & TLR2)	Average gross power ECOMAX	kW	2.512	2.656	2.476
	Power consumed by ancillary	kW	25,76	37,02	34,25
	Electric energy produced	kWh	1.868.668	1.784.654	1.839.423
	Average gross power TLR2	kW	0	0	0
	Electric energy produced	kWh	0	0	0
	Methane consumed by ECOMAX	Sm^3	525.379	501.758	517.157
	Methane consumed TLR2	Sm^3	0	0	0
	Total methane consumed	Sm^3	525.379	501.758	517.157
Electricity produced by photovoltaic	50 kW	kWh	2.414	3.590	5.791
	282 kW	kWh	5.298	8.798	26.073
	993 kW	kWh	24.917	34.963	87.438
	994 kW	kWh	17	14	18
	Self-consumption	kWh	7.713	12.388	31.863
	Cession	kWh	24.934	34.978	87.456

Biomethane	Biomethane produced	Sm^3	1.496.905	1.715.425	1.819.642
	Biomethane in SNAM	Sm^3	992.436	1.215.328	1.226.146
	Biomethane for vehicle	Sm^3	504.248	499.972	592.256
Biogas	Biogas used to produce biomethane	Sm^3	2.376.040	2.722.897	2.888.321
	Total biogas produced	Sm^3	5.083.546	5.051.455	4.723.665
Total power need	Average power need	kW	6.645	7.281	7.128
CO_2 production	CO_2 total production	kg	454.110	416.260	665.920

Table 5: energy profile from April to June.

YEAR 2022			Apr-22	May-22	June-22
Methane price	PSV	€/MWh	104,154	91,599	105,152
		€/Sm^3	1,140	1,002	1,151
		cost CH_4/PSV CH_4	1,028	1,056	1,059
Electricity price	PUN	€/MWh	245,970	230,060	271,310
		cost E.E./PUN E.E.	0,723	0,766	0,654
Purchased methane	Quantity	Sm^3	377.335	393.026	193.641
	Total cost	€	442.011 €	416.146 €	236.023 €
	Price for Sm^3	€/Sm^3	1,171	1,059	1,219
Purchased electricity	Quantity	kWh	2.446.453	3.361.906	3.307.791
	Total cost	€	435.011 €	592.434 €	587.332 €
	Price for kWh	€/kWh	0,178	0,176	0,178

Biogas engine production	Electric energy production SESA 1-2-4-5-3	kWh	560.208	475.798	1.377.409
	Electric energy production BIO 6	kWh	475.584	443.316	222.093
	Biogas used	Sm^3	462.245	410.175	713.813
	Electric energy production BIO 1-2-3-4	kWh	1.745.770	465.673	607.155
	Biogas used	Sm^3	779.934	209.173	285.230
	Electric energy production BIO 5	kWh	1.894	3.039	31.984
Methane engine production (ECOMAX & TLR2)	Average gross power ECOMAX	kW	2.034	1.973	885
	Power consumed by ancillary	kW	30,72	46,69	30,59
	Electric energy produced	kWh	1.464.414	1.468.067	637.342
	Average gross power TLR2	kW	0	0	0
	Electric energy produced	kWh	0	0	0
	Methane consumed by ECOMAX	Sm^3	411.722	412.749	179.190

	Methane consumed TLR2	Sm^3	0	0	0
	Total methane consumed	Sm^3	411.722	412.749	179.190
Electricity produced by photovoltaic	50 kW	kWh	6.847	6.995	7.178
	282 kW	kWh	31.781	27.825	27.396
	993 kW	kWh	98.643	93.240	128.182
	994 kW	kWh	19	19	19
	Self-consumption	kWh	38.629	34.819	34.575
	Cession	kWh	98.662	93.259	128.202
Biomethane	Biomethane produced	Sm^3	1.649.979	2.438.155	2.039.947
	Biomethane in SNAM	Sm^3	1.126.702	1.837.178	1.453.913
	Biomethane for vehicle	Sm^3	523.107	600.187	585.919
Biogas	Biogas used to produce biomethane	Sm^3	2.619.014	3.870.087	3.238.011
	Total biogas produced	Sm^3	3.861.193	4.489.436	4.237.054
Total power need	Average power need	kW	6.818	7.688	7.756
CO_2 production	CO_2 total production	kg	554.700	580.420	825.850

Table 6: energy profile of July and August.

YEAR 2022			July-22	Aug-22
Methane price	PSV	€/MWh	174,692	232,658
		€/Sm^3	1,912	2,546
		cost CH_4/PSV CH_4	1,140	1,021
Electricity price	PUN	€/MWh	441,650	543,150
		cost E.E./PUN E.E.	0,417	0,326
Purchased methane	Quantity	Sm^3	333.004	279.637
	Total cost	€	726.102 €	726.820 €
	Price for Sm^3	€/Sm^3	2,180	2,599
Purchased electricity	Quantity	kWh	2.892.182	3.298.945
	Total cost	€	532.868 €	583.421 €
	Price at kWh	€/kWh	0,184	0,177
Biogas engine	Electric energy production SESA 1-2-4-5-3	kWh	1.708.140	1.875.289
	Electric energy production BIO 6	kWh	127.080	197.509
	Biogas used	Sm^3	819.008	925.033
	Electric energy production BIO 1-2-3-4	kWh	204.099	12.978
	Biogas used	Sm^3	128.824	25.945

	Electric energy production BIO 5	kWh	97.676	45.160
Methane engine (ECOMAX & TLR2)	Average gross power ECOMAX	kW	260	906
	Power consumed by ancillary	kW	12,59	24,82
	Electric energy produced	kWh	193.241	673.755
	Average gross power TLR2	kW	1.386	536
	Electric energy produced	kWh	1.024.355	398.492
	Methane consumed by ECOMAX	Sm^3	54.330	189.427
	Methane consumed TLR2	Sm^3	279.903	110.167
	Total methane consumed	Sm^3	334.233	299.594
Electricity produced by photovoltaic	50 kW	kWh	7.679	5.134
	282 kW	kWh	24.236	19.627
	993 kW	kWh	118.994	81.134
	994 kW	kWh	20	20
	Self-consumption	kWh	31.914	24.761
	Cession	kWh	119.013	81.154
Biomethane	Biomethane produced	Sm^3	2.244.590	2.724.606

	Biomethane in SNAM	Sm^3	1.714.581	2.157.291
	Biomethane for vehicle	Sm^3	529.941	567.121
Biogas	Biogas used to produce biomethane	Sm^3	3.562.841	4.324.771
	Total biogas produced	Sm^3	4.510.674	5.275.749
Total power need	Average power need	kW	8.013	8.366
CO_2 production	CO_2 total production	kg	1.699.010	1.949.660

Once the energy profile was built, it was possible to proceed with the study, starting from the analysis of all the boundary conditions and the variables to be considered.

5. The logic of the analysis

The analysis conducted aims to make a comparison from January until August to understand if the company has been able to achieve maximum efficiency or not based on the operational choices made.

The analysis considers three energy carriers to meet the energy needs of the company:

- Consumption of electricity purchased from the grid;
- Consumption of methane purchased from the grid to produce electricity;
- Consumption of self-produced biogas to run SESA engines for electricity production.

Intentionally, as required by the company, thermal energy was not considered within the analysis. Also diesel and biomethane consumption were not considered within the analysis, since this two last concern with transport and not plants, that are the focus of the analysis.

Regarding the biogas produced, the study then considers the three different uses that the company can make of it:

- production of electricity for self-consumption;
- production of electricity for sale;
- production of biomethane and CO_2 for vehicle power and sale.

The final aim is to identify which combination between the choice of energy carrier and the end use of biogas is the best from an economic and environmental point of view, considering all the variables and boundary conditions. The photovoltaic system also contributes to generating electricity to be used within the company, but, since each photovoltaic plant is designed to use the electricity generated only in self-consumption or only for sale, it is not possible to decide whether to use the energy generated to use it within the site or sell it. Therefore, depending on the season, the 50 kW and 282 kW photovoltaic systems will simply decrease the company's energy needs by a small amount, while the two 993 kW and 994 kW plants will always generate an economic income. The same for engine BIO 5: since its biogas comes from agricultural biomass and not from biowaste, all the biogas produced by the biodigester connected to it is used to run the cogenerator for electricity production. So, its situation is the same in real operating conditions and in hypotetical operating conditions.

Regarding the three main energy carriers, however, the company has full decision-making freedom in preferring one source rather than another, generating very different situations. The same applies to the use of biogas from waste: it is the company that decides how to use it.

An effective example to better understand the objective of the study is the following: in July, is it better to buy the maximum possible amount of electricity and make up for the lack of power by buying fossil methane or turning on biogas engines? Or is it better to produce electricity using methane engines at full capacity and use biogas only to produce biomethane? The more general question to ask therefore becomes: which energy carrier is the best to meet the energy needs of the site and which use of biogas is most suitable?

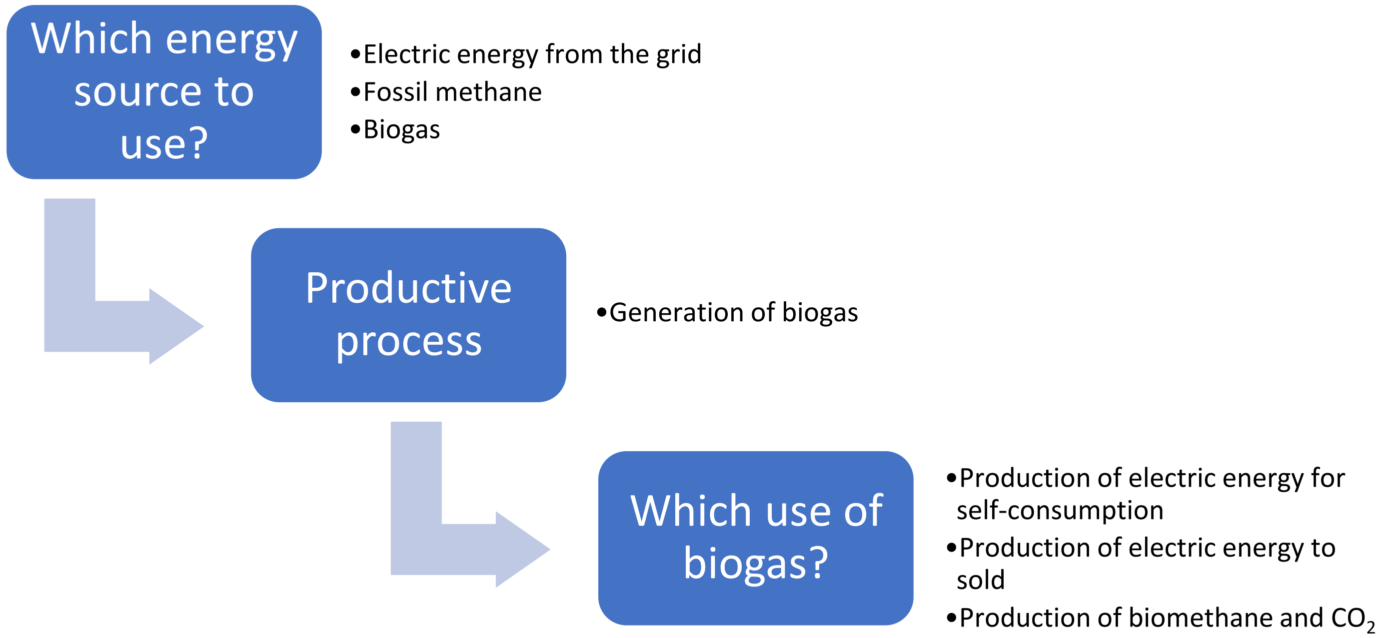

Figure 7: logical scheme at the base of the analysis.

In the following pages, all possible choices have been analyzed, considering all variables, boundary conditions, plant limits and everything relevant to the analysis.

6. The boundary conditions

Of fundamental importance in carrying out a detailed study was the identification and analysis of all the boundary conditions, i.e. identifying the electricity and methane contracts with the related costs and withdrawal limits, the maximum power of each individual engine (both biogas and methane) with the related maintenance contracts and efficiencies, the limits of the biogas treatment plant, the maximum production of biomethane and CO_2, the maximum quantity of biomethane that can be introduced into the network, the identification of the incentive for the sale of electricity generated by BIO engines and photovoltaic plants and the percentage of methane and CO_2 present in biogas, the identification of the incentive for the sale of biomethane produced as well as the daily prices of electricity and methane purchased.

The purchase cost of electricity and methane is of crucial importance to determine in which operating conditions the plant, as a whole, is able to generate the maximum "Gain-Cost" difference. As will be seen below, electricity and methane prices vary continuously and contracts are often based on these prices, identified as PUN (Single National Price) for electricity and PSV (Virtual Trading Point) for methane. Therefore, a daily price monitoring combined with an analysis such as the one produced allows to determine day by day what are the best choices to make the plant as profitable as possible.

6.1. The PUN and the PSV

Echoing and integrating what was said earlier, PUN is the Italian Power Exchange's wholesale reference price for power purchases. At the Italian Electricity Exchange, active since 2007 following the entry into force of the Legislative Decree governing the liberalization of the electricity market, sales between electricity producers and suppliers are regulated. The PUN represents, as said previously, the national weighted average of the zonal electricity sales prices for each hour and for each day. The national figure is an amount that is calculated on the average of several factors, and that takes into account the quantities and prices formed in the different areas of Italy and at different times of the day. (Enel Energia, 2022)

According to SNAM, the PSV is the "*virtual point located between the Entry Points and the Exit Points of the National Gas Pipeline Network, where users and other authorized parties can carry out, on a daily basis, exchanges and transfers of gas injected into the* *national network."* Therefore, the PSV serves as the primary nexus of the Italian gas market's supply and demand. (Luce – Gas, 2022)

For the analysis carried out, the PUN and PSV values reported in the "Gestore Mercati Energetici" portal were considered and are shown below.

Table 7, table 8, table 9 and table 10 show prices of electricity and methane in previous years and current prices. According to GME (Gestore Mercati Energetici), as visible, the cost of energy, both electricity and methane, as mentioned at the beginning, has grown dramatically compared to previous years.

Table 7: PUN values of previous years, in €/MWh.

Period	Purchase price PUN (€/MWh)
2004	51,60
2005	58,59
2006	74,75
2007	70,99
2008	86,99
2009	63,72
2010	64,12
2011	72,23
2012	75,48
2013	62,99
2014	52,08
2015	52,31
2016	42,78
2017	53,95
2018	61,31
2019	52,32
2020	38,92
2021	125,46

Table 8: PUN values in 2022 from January to August, in €/MWh.

Period	Purchase price PUN (€/MWh)
January-2022	224,50
February-2022	211,69
March-2022	308,07
April-2022	245,97
May-2022	230,06
June-2022	271,31
July-2022	441,65
August-2022	543,15

(source: GME - Gestore dei Mercati energetici spa*,* 2022)

Table 9: PSV values of previous years.

Thermal Year	Average price PSV (€/MWh)	Average price (€/Sm^3)
Oct-10 ÷ Sep-11	25,857	0,283
Oct-11 ÷ Sep-12	29,457	0,322
Oct-12 ÷ Sep-13	26,800	0,293
Oct-13 ÷ Sep-14	-	-
Oct-14 ÷ Sep-15	-	-
Oct-15 ÷ Sep-16	-	-
Oct-16 ÷ Sep-17	18,975	0,208
Oct-17 ÷ Sep-18	23,109	0,253
Oct-18 ÷ Sep-19	19,148	0,210
Oct-19 ÷ Sep-20	10,678	0,117
Oct-20 ÷ Sep-21	24,570	0,269

Table 10: PSV values from October 2021 to August 2022.

Period	Average price PSV (€/MWh)	Average price (€/Sm^3)
October-21	88,234	0,966
November-21	80,310	0,879
December-21	113,344	1,240
January-22	86,909	0,951
February-22	82,832	0,907
March-22	128,317	1,404
April-22	104,154	1,140
May-22	91,599	1,002
June-22	105,152	1,151
July-22	174,692	1,912
August-22	232,658	2,546

(source: GME - Gestore dei Mercati energetici spa, 2022)

To convert the price of methane from €/MWh to €/Sm^3, is necessary to divide the value expressed in €/MWh for a coefficient equal to 91,37065, according to SNAM convertitor.

Not only that, prices are also subject to high variability, with important differences even between one day and the next. As a result, the company began to monitor prices day by day to have even more awareness of its expenses and be able to better manage them.

6.2. Contracts for the supply of electricity and methane

The company has stipulated:

- a contract for the supply of electricity that lasts throughout the year 2022;
- a contract for the supply of methane (hereinafter referred to as methane1), that lasts throughout the year 2022;
- a second contract for the supply of methane that lasts from July 2022 until September 2022. The reason for this last contract is immediately explained: following the installation in the summer of this year of the 4500 kW engine (previously called TLR2), the company has stipulated, since there are limits on the maximum amount of methane withdrawal, a second contract (hereinafter

methane2) to ensure the supply of methane also for the latter. As regards duration, gas contracts can be based on the thermal year: reference period that runs from 1 October to 30 September following.

The electricity contract shall set out the following conditions:

Period from 01/01/2022 to 31/03/2022

For the supply of electricity, the following fees are invoiced to the company:

- *Price for the energy component determined on the basis of the Single National Price (PUN) according to the following formula:*

$$P = PUN * (1 + \lambda) + \alpha$$

Where:

- *PUN is the arithmetic average of the Single National Price (PUN) published by the "Gestore Mercati Energetici" (GME) on the website www.mercatoelettrico.org for the reference month and calculated on the hourly PUN.*
- *λ is the value of network losses quantified as established by ARERA (currently equal to 3.8% for medium voltage supplies)*
- *α is the value of the spread applied to the offer, including network losses, equal to 0,00104 €/kWh*

Finally, dispatching fees are applied as defined by Articles. 24 and 25 of the "Integrated text of the dispatching service (TIS)" approved by ARERA with Resolution ARG/elt/ 107/09 and subsequent amendments, taking into account network losses.

Period from 01/04/2022 to 31/12/2022

For the supply of electricity, the following fees are invoiced to the company:

- *Price for the energy component net of network losses, fixed and invariable for the entire contract period, equal to:*

Table 11: price for the energy component net of network losses.

Band	Price
Band F1 (Monday – Friday, from 8 a.m. to 7 p.m., excluding holidays)	0,14746 €/MWh
Band F2 (Monday – Friday, from 7 a.m. to 8 a.m. and from 7 p.m. to 11 p.m., Saturday from 7 a.m. to 11 p.m.)	0,14808 €/MWh
Band F3 (Monday – Friday, from 11 p.m. to 7 a.m., Sunday and holidays)	0,13202 €/MWh

- *This price, expressed gross of network losses pursuant to ARERA Resolution 426/202/R/com and subsequent amendments (currently equal to 3.8% for medium voltage supplies) is equal to:*

Table 12: price expressed gross of network losses.

Band	Price
Band F1 (Monday – Friday, from 8 a.m. to 7 p.m., excluding holidays)	0,15306 €/MWh
Band F2 (Monday – Friday, from 7 a.m. to 8 a.m. and from 7 p.m. to 11 p.m., Saturday from 7 a.m. to 11 p.m.)	0,15371 €/MWh
Band F3 (Monday – Friday, from 11 p.m. to 7 a.m., Sunday and holidays)	0,13704 €/MWh

Finally, dispatching fees are applied as defined by Articles. 24 and 25 of the "Integrated text of the dispatching service (TIS)" approved by ARERA with Resolution ARG/elt/ 107/09 and subsequent amendments, taking into account network losses. [1]

In addition, the maximum annual withdrawal of kWh from the grid is equal to 30.000.000 kWh/year; when this value is exceeded, the company will no longer pay with the fixed price method but will pay on a PUN basis method.

So, briefly summarizing what is stated in the contract:

[1] Extract taken directly from the electricity supply contract.

- From January to April, the price of electricity is based on the PUN. The ratio between price of electricity effectively paid by the company (that take into account also dispatching fees) and the PUN is on average 1,23.
- From May to the end of the year, the price of electricity is fixed to an average of 0,15 €/kWh plus management fees. The final price is 0,18 €/kWh.
- The maximum limit of kWh that can be withdrawn throughout the year is 30.000.000 kWh: once the maximum quantity has been exceeded, the fixed tariff will no longer be applied, but the price will be recalculated on a PUN basis.

As regards the contract methane1, it lays down the following conditions:

For the supply of natural gas, the following fees are invoiced monthly to the company:

- *Price for the raw material fixed and invariable for 12 months equal to:*

$$\text{Share proportional to consumption} = PSV_{DA\_MM} + \alpha \ (€/Sm^3)$$

Where:

- *α is the value of the spread applied to the offer, equal to 0,01 €/Sm^3;*
- *PSV_{DA_MM} is equal to the arithmetic mean of the daily quotes "Heren Day Ahead Price" expressed in €/MWh and converted into €/Sm^3 on the basis of a multiplicative coefficient equal to 0,0105833.*

For each day of the withdrawal month, the quotation "Heren Day Ahead Price", expressed in €/MWh, is the "Offer" price relating to the "DAY-ahead" period published under the title "PSV PRICE ASSESSMENT" in the "ICIS Heren European Spot Gas Markets" report of the nearest previous working day according to the English calendar, which refers to the following quotations:

- *"DAY Ahead" if the day in question is a working day according to the English calendar;*
- *Weekend, if the day in question is not a working day according to the English calendar.*

For the purpose of determining the price, it is specified that each monthly average will PSV_{DA_MM} be rounded to the fifth decimal place.

With reference to the 4th Quarter of 2021, the above fees represent approximately 0% of the total expenditure for a typical customer, net of taxes.

- *The fixed fee, equal to:*

$$\text{Fixed fee} = Cb * CG \text{ €/Sm}^3$$

Where:

Cb = 0,2386 €/month per Sm^3/day

CG = 27.000 daily capacity expressed in Sm^3/day

With reference to the 4th Quarter of 2021, this consideration represents approximately 44% of the total expense for a typical customer, net of tax.

- *The added fees CRVi, CRVos, CRVbl, CRVst and CRVg determined by ARERA. In addition, any new fees that may be introduced by ARERA itself during the term of this contract will be applied on the invoice.*
- *Maximum daily withdrawn equal to 27.000 Sm^3/d. If exceeded:*

Table 13: Penalty exceeding daily quantity.

Penalty exceeding daily quantity	
Up to 10%	0 €/Sm^3
Over 10%	3,46 €/Sm^3

In addition, for redelivery points (PDR) connected to the local distribution networks, the invoice will apply the fees to cover distribution and metering services, transport as well as all additional components intended to cover general charges and other components of the gas sector. These fees are established and periodically updated by ARERA. [2]

Summarizing and simplifying what is reported in the contract:

- Price is calculated on the basis of PSV. The ratio between price of methane effectively paid by the company (that take into account also dispatching fees) and the PSV is on average 1,06.

[2] Extract taken directly from the first methane contract, identified as methane1.

- Daily capacity, i.e. the maximum limit of methane that can be withdrawn daily set at 27.000 Sm^3. Once the threshold increased by 10% is exceeded, the price will no longer be the one previously established but will be a fixed price of 3,40 €/Sm^3.

Finally, the contract mehtane2 establishes the following conditions:

- *Reference contract volume*

Table 14: maximum withdrawal limit for each month of the contract.

Month	July-22	August-22	September-22
VRift	775.000 Sm^3	775.000 Sm^3	775.000 Sm^3

Price

The Price consists of the following contractual parameters:

a) a monthly fee T, expressed in €/month, for each delivery and/or redelivery Point and calculated according to the following formula:

T=TF+TV

where:

▪ *TF = [Cg x (CPu+ CMT + CMCF)] / 12*

▪ *TV = (CVu + CVFC) x Vt*

▪ *Cg = 25.000 Sm^3/d*

- Cg is the volume of gas expressed in Sm^3/d that the supplier undertakes to make available daily to the company at the Delivery and/or Redelivery Points and that the company has the right to withdraw during the supply period according to the terms and conditions of the contract.

- the CPu, CMT, CMCF, CVu and CVFC parameters are defined by the "Regolazione tariffaria per il servizio di trasporto e misura del gas naturale per il quinto periodo di regolazione 2020 – 2023 (RTTG 2020 – 2023)", attached to the ARERA Decree. 114/2019/R/GAS;

- Vt is the volume collected monthly from each delivery and/or redelivery Point.

b) a Pd unit quota, expressed in c€/Sm³, applied to the volumes collected daily from each Delivery and/or Redelivery Point defined as follows:

$P_d = P_{0,d} + I_d$

where:

$P_{0,d}$ *= unit fee differentiated by supply period as shown in the Daily Price Table.*

Table 15: Daily Price Table.

Supply period		$P_{0,d}$ (c€/Sm³)
From	To	
01/07/2022	01/10/2022	0,500

I_d *= daily quotation of PSV DA in €/MWh, converted to c€/Smc multiplying it by 1,05833, relative to the day "d". For each day "d" the daily quote is the average of the 'Bid' and 'Offer' prices published in the 'ICIS Heren European Spot Gas Markets' report under the title 'PSV Price Assessment', of the nearest previous working day according to the English calendar, with reference to the following quotations: "Day Ahead" if day "d" is working and "Weekend" if day "d" is non-working.*

The following are to be charged to the company and excluded from the price:

a) the additional tariff components of the transport tariff to cover the general charges of the gas system;

b) any additional tariff component introduced by ARERA subsequently.

Daily capacity overruns

The company undertakes to keep the daily Pg withdrawals relating to the individual Delivery and/or Redelivery Points covered by the supply below the daily capacity Cg.

If in a month of withdrawal the maximum value drawn relative to a PDR is higher than the defined Cg daily capacity, the company in addition to the monthly amounts must pay, as a penalty, for each cubic meter over the indicated tolerance of the corresponding band, the amount calculated on the basis of the formulas shown in the following list.

− Penalty = 0 [€/Sm³] in case of exceeding up to 10%

− Penalty = 1,10 x CPu [€/Sm³] in case of exceeding more than 10%. [3]

So, briefly summarizing what is stated in the contract:

- Price is calculated on the basis of PSV. The ratio between price of methane effectively paid by the company and the PSV is on average 1,06.
- Maximum daily withdrawal limit set at 25.000 Sm³.
- Penalty calculated multiplying the coefficient CPu for 1,10.

The methane withdrawal limits have been put for completeness but, even if engines were running at full power all day, the maximum withdrawal threshold would never be exceeded.

Table 16: contracts conditions summary.

Supply	Price	Withdrawal limit	Penal	Duration
Electrical energy	- From January to April: based on PUN - From May to December: 0,18 €/kWh	30.000.000 kWh/year	No more fixed price but price on PUN basis	On PUN basis: January 2022 – April 2022 Fixed price: May 2022 - December 2022
Methane	Based on PSV	27.000 Sm³/d	3,40 €/sm3	January 2022-December 2022
Methane	Based on PSV	25.000 Sm³/d	1,10 * CPu	July 2022 – September 2022

6.3. Engines

In the following paragraph the data relating to the power of each engine previously illustrated are resumed and integrated with further data used in the analysis.

From the technical data sheets of the engines and according with company's historical data it was decided, as a precaution, to assume the lowest efficiency values reported in the manuals. Since the engines are all from the same manufacturer and only change

[3] Extract taken directly from the second methane supply contract identified as methane2.

the powers, it was therefore decided to assume an efficiency of 38% for each engine, as reported in technical datasheets.

In addition, engines undergo periodic maintenance every number of hours of use. The cost is also established through contracts and is fixed. For the engines of the SESA and BIO groups, the cost is 9,78 euro for each hour of use, while for the ECOMAX the price is 28,78 €/h. For the TLR2 engine, having been installed recently and having been used little, there is still no contract that determines a cost based on the hours of use; so, since the engine is very similar to the ECOMAX, we assumed the same cost of maintenance.

A further parameter that was decided to consider in the analysis is the amount of energy absorbed by the engines, commonly defined as "energy consumed by ancillary services". It has been seen by analyzing the production data of the engines that, in fact, the total energy produced by the engines is always slightly higher than that which is effectively used within the site/sold. This is because engines self-consume a small amount of energy for ancillary services, such as screens, remote reading services, meters. BIO engines ancillary services consume 6,6% of the energy produced, SESA engines ancillary services consume 8,82% of the energy produced and ECOMAX engine ancillary services consume 2,4% of the energy produced. Regarding TLR2, since few values are available, the same value of ECOMAX was considered.

The following table summarizes the data used.

Table 17: engines characteristics summary.

Engine	Electric power	Efficiency	Feeding	Maintenance	Ancillary services
SESA 1	1064 kW	38%	Biogas	9,78 €/h	8,82 % of total produced energy
SESA 2	1416 kW				
SESA 3*	1416 kW				
SESA 4	1415 kW				
SESA 5	1415 kW				
BIO 1	998 kW	38%	Biogas	9,78 €/h	6,6 % of total produced energy
BIO 2	998 kW				
BIO 3	998 kW				
BIO 4	998 kW				
BIO 5*	999 kW				
ECOMAX	3000 kW	38%	Fossil methane	28,78 €/h	2,4 % of total produced energy
TLR2	4500 kW	38%	Fossil methane	28,78 €/h	2,4 % of total produced energy

**Remember that SESA 3 and BIO 5 run using biogas that comes from landfill and agricultural biomass, respectively.*

6.4. The production of biomethane and CO_2

The production of biomethane and CO_2 are closely correlated with the quantity and quality of biogas available. Moreover, since the company also needs to produce thermal energy for its own needs (biodigester heating) and for the users connected to it, and to produce electricity, the amount of biogas available to produce biomethane and CO_2 depends also on the quantity of biogas used to power SESAs and BIOs. Therefore, lower biogas availability is expected in the winter months as it is used in the production of thermal and electrical energy.

Moreover, from what has been verified by the analysis of the real situation of the production plant, the actual production capacity of the plant is lower than the nominal one of 1000 Sm^3/h, obtaining a real production capacity of maximum 4000 Sm^3/h.

As far as CO_2 production is concerned, it is directly related to biomethane production, being CO_2 obtained as the second product from biogas treatment. Once the separation between biomethane and CO_2 has taken place downstream of the treatment plant, it is, as mentioned in the previous paragraphs, liquefied, stored and analyzed. The CO_2 is then sold by means of tanks transported on semi-trailers.

The composition of the biogas is decisive for the analysis to quantify the power developed by the engines and/or the amount of biogas consumed by them on the basis of the required power.

In the study carried out, it was decided, on the basis of the data obtained by analyzing biogas on a daily basis, to assume the composition of the biogas as shown in *Table 18.*

Table 18: biogas composition.

Biogas composition		
63% methane	36% CO_2	1% other gases

About the calorific value of methane, it was decided to use the lower average calorific value provided by SNAM through the reports sent regularly, equal to 9,36 kWh/Sm^3.

6.5. Revenues

Being part of the energy produced sold in the form of electricity and biomethane, the company has entered sales contracts/incentives with various operators.

For the electricity produced by BIO engines and photovoltaic systems for the sale of electricity, the proceeds are equals to 0,28 €/kWh.

Regarding the sale of biomethane, the company obtained an incentive calculated in the following way:

- the biomethane produced by S.E.S.A. is classified as advanced biomethane as it is produced from the materials listed in part A of Annex 3 of the DM 10 October 2014 and subsequent amendments (biowaste from domestic collection). Producers of advanced biomethane are awarded a value of € 375 for each CIC (Certificates of Release for Consumption, in italian “Certificati di Immissione in Consumo”) recognized. In the case of advanced biomethane, 1 CIC corresponds to 5 Gcal, and 5 Gcal corresponds to 615 Sm^3 of biomethane. Therefore, for every 615 Sm^3 of recognized biomethane produced, the company receives € 375. Making the ratio between the two values, the value of the incentive is therefore equal to 0,609756 €/Sm^3. (GSE, 2022)

Regarding the final sale of biomethane, the company has two different revenues:

a) biomethane sold through intermediary to S.E.S.A. partnerships is sold at the price of 0,60 €/Sm^3, to which must be added the incentive of 0,609756 €/sm^3, for a final price of 1,2 €/Sm^3;
b) biomethane sold through the SNAM network is instead sold considering

$$\frac{PSV\ biomethane\ sale\ of\ the\ i-month}{91{,}37065}\frac{€}{Sm^3}+0{,}609756\frac{€}{Sm^3}$$

Where "PSV biomethane sale of the i-month" is the sale price of biomethane reported on the GME portal, equal to the average PSV of the reference month and decreased by 5%. The maximum quantity of biomethane sold through the SNAM network with the incentive is 84.000 Sm^3/d by contract. The excess is sold without incentive.

For CO_2, on the other hand, the average selling price is 110 €/ton.

Table 19: revenues summary.

Product	Revenue
Electricity produced by photovoltaic system	0,28 [€/kWh]
Electricity produced by BIO engines	0,28 [€/kWh]
Biomethane for S.E.S.A. partners	0,60 + 0,609756 [€/Sm^3]
Biomethane sold through SNAM network < 84.000 Sm^3/d	PSV reported on GME portal [€/Sm^3] + 0,609756 [€/Sm^3]
Biomethane sold through SNAM network in addition to 84.000 Sm^3/d	PSV reported on GME portal [€/Sm^3]
CO_2	110 [€/t]

7. The analysis

At this point it is possible to explain in detail how the study was structured.

Starting from the information collected in the previous chapters, it was decided to create all the hypothetical operational situations that may occur within the company, including the real situation. In this way it was possible to compare every possible alternative with what the company did and establish what the margins for improvement were.

Five different hypothetical situations have been identified, plus the real case. Within each hypothetical situation, the different possible operating conditions were then developed starting from the initial condition imposed.

The situations identified are as follows:

- Real case: each data coincides with what the company effectively did in the i - month.
- Case "SESA engines switched off": in this case we went to analyze how the situation varies if the biogas used to power the SESA engines were used differently.
- Case "BIO engines switched off": similar to the previous case, here too we analyzed how the situation varies if the biogas used to power the BIO engines were used differently.
- Case "minimum production of biomethane": in this situation we analyze how the situation varies if the minimum amount of biomethane to be sold through the SNAM network is produced and biogas is used to power BIO engines and/or SESA engines.
- Case "maximum production of biomethane": in this situation it is assumed that the biomethane production line is operating at full capacity, and the remaining biogas that cannot be used because the plant, as seen above, has a maximum production limit, was used to power the BIO and/or SESA engines.
- Case "maximum purchase of energy": in this last case we analyze how the situation varies if the company provides for its needs by purchasing as much energy as possible in the form of electricity and/or methane and the production of biomethane is maximum.

The boundary conditions are the same for each case analyzed; they are listed below:

Table 20: boundary conditions, equal for each case.

% CH_4 in biogas	63 %
% CO_2 in biogas	36%
Other gases in biogas	1 %
Engines efficiency	38 %
CH_4 calorific value	9,36 kWh/Sm^3
Incentive on electricity sold	0,28 €/kWh
Biomethane revenue (only for S.E.S.A. partners)	1,209756 €/Sm^3

In addition to the above conditions, there are further conditions that vary from month to month, as follows:

- Amount of biogas produced
- Energy demand
- Price of electricity for purchase
- Methane price for purchase
- Biomethane revenue (sold through SNAM network)

Table 21: fixed boundary conditions for each month on the left and boundary conditions that vary month by month on the right.

Fixed conditions for each month	**Conditions that vary according to the month**
% CH_4 in biogas	Sm^3 of biogas produced
% CO_2 in biogas	Energy demand
Other gases in biogas	Electric energy price
Engines efficiency	Methane price
CH_4 calorific value	Biomethane revenue (sold through SNAM network)
Incentive on electricity sold	
Biomethane revenue (only for S.E.S.A. partners)	

7.1. Equations used

Before explaining in detail all the cases, since the equations used are always the same, they are reported in this paragraph to avoid repetitions.

1. To estimate the quantity of biogas consumed by SESA and BIO engines, the following equation was used:

$$\frac{Sm^3}{h} \, of\ biogas = \frac{Engine's\ power}{Engine\ efficiency * percentage\ of\ methane\ in\ biogas * methane\ c.v.}$$

- *Engine's power [kW]*
- *Engine efficiency equals to 38%*
- *Percentage of methane in biogas equals to 63%*
- *Methane c.v. = methane calorific value, equal to 9,36 kWh/Sm*^{3}

2. To calculate the power generated by engines SESA and BIO, the following equation was used:

$$Engine's\ power = biogas\ available * engine\ efficiency * \%\ of\ methane * methane\ c.v.$$

- *Engine's power [kW]*
- *Biogas available [Sm*^{3}*/h]*
- *Engine efficiency equals to 38%*
- *% Methane means the percentage of methane present in the biogas, equal to 63%*
- *Methane c.v. = methane calorific value, equal to 9,36 kWh/Sm*^{3}

Maximum power for SESA engines is 6726 kW and for BIO (excluding BIO 5) engines is 3992 kW; if the available biogas is higher than the required for the maximum power, it will be used for other purposes.

3. To calculate the quantity of methane needed by ECOMAX and TLR2, the following equation was used:

$$\left(\frac{Sm^3}{h}\right) of\ methane = \frac{Power\ generated\ by\ the\ engine}{efficiency\ of\ the\ engine * calorific\ value\ of\ methane}$$

- *Power generated by the engine [kW]*
- *Efficiency of the engine equals to 38%*
- *Calorific value of methane equals to 9,36 kWh/Sm*^{3}

4. The quantity of kWh produced, knowing the power generated by engines:

$$kWh = kW * h$$

5. The quantity of biomethane produced by the plant is equal to:

$$Biomethane\left(\frac{Sm^3}{d}\right) = \left(\frac{Sm^3}{d}\right) of\ biogas * percentage\ of\ methane\ in\ biogas$$

If the biogas available exceed the maximum capacity of the line for the biomethane production, the maximum quantity of biomethane produced in one day is assumed equals to:

$$Biomethane\left(\frac{Sm^3}{d}\right) = 4000\left(\frac{Sm^3}{h}\right) * 24\ (h)$$

6. Regarding the quantity of CO_2 produced by the plant, it is directly correlated with the quantity of biomethane produced. Assuming, as seen above, that the percentage of CO_2 in biogas is 36%, the quantity of CO_2 produced is:

$$\left(\frac{Sm^3}{d}\right) of\ CO_2 = \left(\frac{Sm^3}{d}\right) of\ biogas * percentage\ of\ CO_2\ in\ biogas$$

Since the CO_2 at the exit of the biomethane treatment line is at 15° C and atmospheric pressure, its density is equal to 1,87 kg/m^3 (Linde – gas, 2022), and since the efficiency of CO_2 treatment plant is equal to 50%, the equation used to find tons of CO_2 sold is:

$$\left(\frac{t}{d}\right) of\ CO_2 = \frac{Sm^3}{d} of\ CO_2 * 1{,}87\frac{kg}{Sm^3} * 0{,}5$$

7. To determine costs of electricity and methane purchased, equations are:

$$Total\ cost\ of\ electricity\ (€/d) = (\frac{kWh}{d})\ purchased * \left(\frac{€}{kWh}\right)$$

$$Total\ cost\ of\ methane\ (€/d) = (\frac{Sm^3}{d})\ of\ methane\ purchased * (\frac{€}{Sm^3})$$

8. Maintenance costs of engines:

$$Maintenance\ costs\ € = maintenance\ costs\ \left(\frac{€}{h}\right) * hour\ of\ running$$

9. Revenues generated:
    - Biomethane in SNAM

$$\left(\frac{€}{d}\right) = \left(\frac{Sm^3}{d}\right) of\ biomethane\ sold * (PSV\ reported\ on\ GME\ portal + 0{,}609756)$$

- $PSV\ reported\ on\ GME\ portal = \frac{PSV\ biomethane\ sale\ of\ the\ i-month}{91{,}37065} \frac{€}{Sm^3}$
- 0,609756 = *incentive, in €/Sm³*
- For the quantity in excess of 84.000 Sm^3/d, the incentive is not considered

    - Biomethane to S.E.S.A. partners

$$\left(\frac{€}{d}\right) = \left(\frac{Sm^3}{d}\right) of\ biomethane\ sold * (0{,}60 + 0{,}609756)(\frac{€}{Sm^3})$$

    - Electricity

$$\left(\frac{€}{d}\right) = \left(\frac{kWh}{d}\right) of\ electricity\ sold * 0{,}28\ \left(\frac{€}{kWh}\right)$$

7.2. The real case

The real case is the simplest case, as there are no assumptions to be made, but a "photograph" of i-month is made to have a reference benchmark to study subsequent cases.

The data entered are the data collected previously, i.e. the data of the company energy profile:

1. Initial conditions of the i-th month

The following have been identified: quantity of biogas produced, energy needs, price of electricity purchased, price of methane purchased.

2. Electricity purchased from the grid

From the electricity bill it was possible to quantify the kWh of electricity purchased and its cost.

3. Operating conditions of SESA engines

Power developed by the engines and their electricity produced (and self-consumed), the amount of biogas used, the operating hours of the engines and maintenance costs.

4. Operating conditions of BIO engines

Power developed by the engines and their electricity produced (and sold), the amount of biogas used, the operating hours of the engines and maintenance costs, the profit generated by the sale of electricity.

5. Operating conditions of the ECOMAX/TLR1 engine

Average power generated by the engine and the electricity produced, operating hours, maintenance costs and the amount of fossil methane consumed.

6. Operating conditions of the TLR2 engine

Average power generated by the engine and the electricity produced, operating hours, maintenance costs and the amount of fossil methane consumed.

7. Electricity generated by photovoltaic systems

Electricity produced by photovoltaic systems, identifying the quantity self-consumed and the quantity sold into the network.

8. Biomethane and CO_2

Quantity of biomethane produced and sold to S.E.S.A. partner companies and through the SNAM network, and the tons of CO_2 produced and sold.

At the end of the analysis of all these parameters, revenues and costs were identified.

7.3. *Case "SESA engines switched off"*

In the first simulated case, the initial situation differs from the real one in assuming SESA engines switched off and using the unused biogas for feeding BIO engines or for the production of biomethane. The following diagram displays all possible situations that can occur:

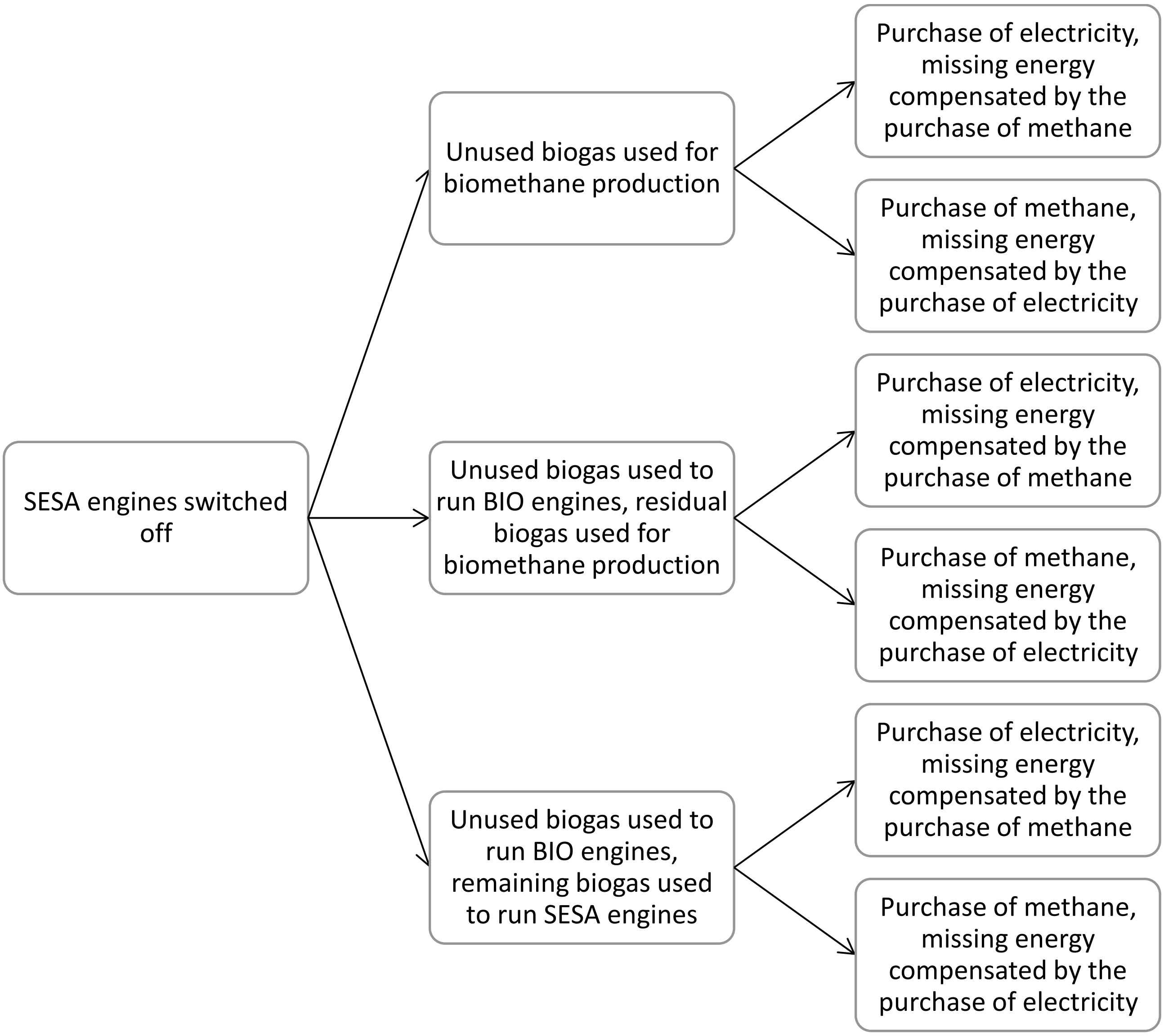

Figure 8: conceptual scheme of the case "SESA engines switched off".

Unused biogas used for the production of biomethane

In this situation it was assumed to keep the SESA engines switched off and then to use the unused biogas to increase the production of biomethane and, consequently CO_2.

What was then done at the level of calculations was to shift the quantity of biogas destined for SESA engines in the production of biomethane and determine the amount of net energy to be purchased from the grid starting from the daily energy needs and subtracting the amount of energy used for self-consumption generated by the photovoltaic system.

Subsequently, as visible in *Figure 9*, two subcases were analyzed:

- purchase of electricity, missing energy compensated with purchase of methane;
- purchase of methane, missing energy compensated with purchase of electricity.

The meaning of these two cases is as follows: knowing the energy needs of the site, the first case assumes that the company provides to meet its energy needs by purchasing electricity from the network and, only if the latter is not sufficient, purchasing methane to make up for the lack of power; the second case presupposes, instead, that the company provides to meet the energy needs by purchasing the amount of methane necessary and by turning on the ECOMAX and/or TLR2 engines and purchasing electricity from the network if the power generated by engines is not sufficient. In conclusion, these two cases are used to identify, on the basis of prices, which energy carrier between electricity from the grid and fossil methane should be purchased by the company to optimize costs.

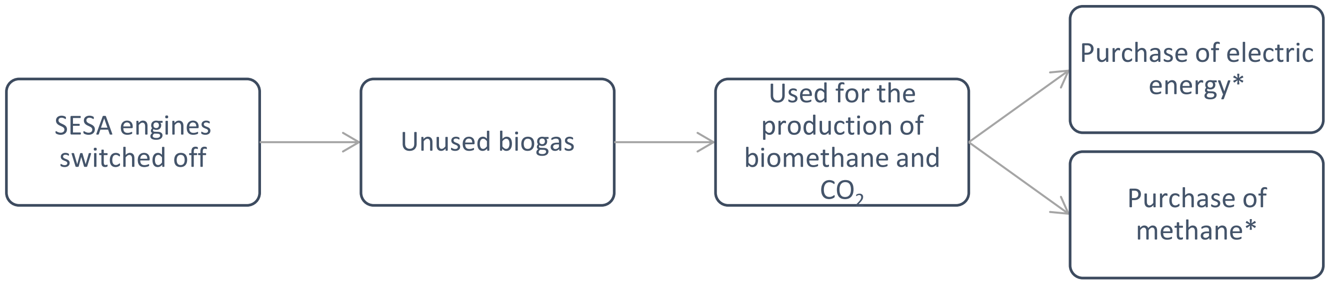

Figure 9: biogas for SESA engines shifted to biomethane production plant.

* for purchase of electricity and purchase of methane is intended as primary energy carrier; therefore, if the maximum electricity that can be purchased from the network is sufficient to meet energy needs, it is not necessary to buy methane (and vice versa).

Unused biogas used to power BIO engines, residual biogas in biomethane

Unlike the previous situation, in this case it is assumed that the amount of unused biogas following the shutdown of the SESA engines is used in BIO engines, allowing them to work at a higher regime and generate more electricity.

- Since BIO engines can develop a maximum total power of 3992 kW, it is clear that they also have a maximum biogas consumption as mentioned before, which, based on the initial conditions assumed, is equal to 1.782 Sm^3/h. Therefore, once the full power of BIO has been reached, if biogas is still available, this, in the case under analysis, has been directed to the biomethane line to increase production of biomethane and CO_2.

As in the previous case, and as in all subsequent cases, the two sub-cases were also developed here:

- purchase of electricity, missing energy compensated with purchase of methane;
- purchase of methane, missing energy compensated with purchase of electricity

to determine which energy carrier should be purchased.

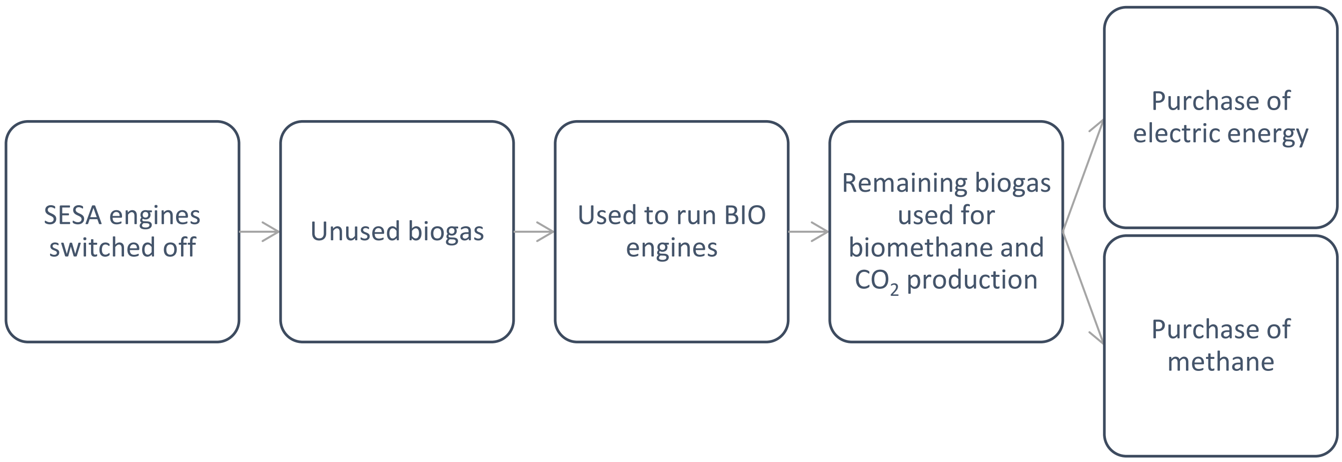

Figure 10: biogas for SESA engines shifted to BIO engines; the remaining quantity used in biomethane production line.

Unused biogas used to power BIO engines, remaining biogas used to power SESA engines

This case is extremely similar to the previous one, with the difference that, while in the case seen above the remaining biogas following the achievement of the maximum power of the BIO engines was used in the biomethane production line, here it is used to power the SESA engines, thus producing electricity to be self-consumed and decreasing the amount of energy to be purchased.

With regard to the purchase of electricity and/or methane, the same considerations made above apply.

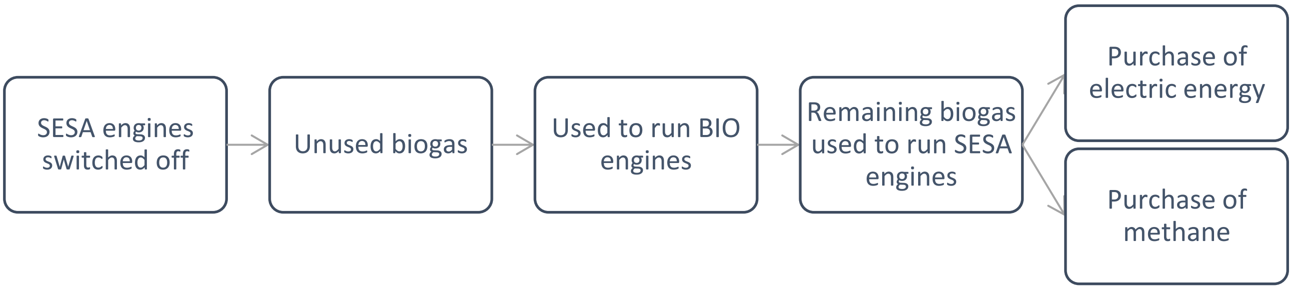

Figure 11: biogas for SESA engines shifted to BIO engines; the remaining quantity used to run SESA engines.

7.4. Case "BIO engines turned off"

In the second simulated case, the initial situation is different in assuming the BIO engines switched off and using the unused biogas to run SESA engines or for the production of biomethane. The study therefore consists of shifting the quantity of biogas allocated in BIO engines to the biomethane line or SESA engines. The following diagram displays all possible situations that can occur:

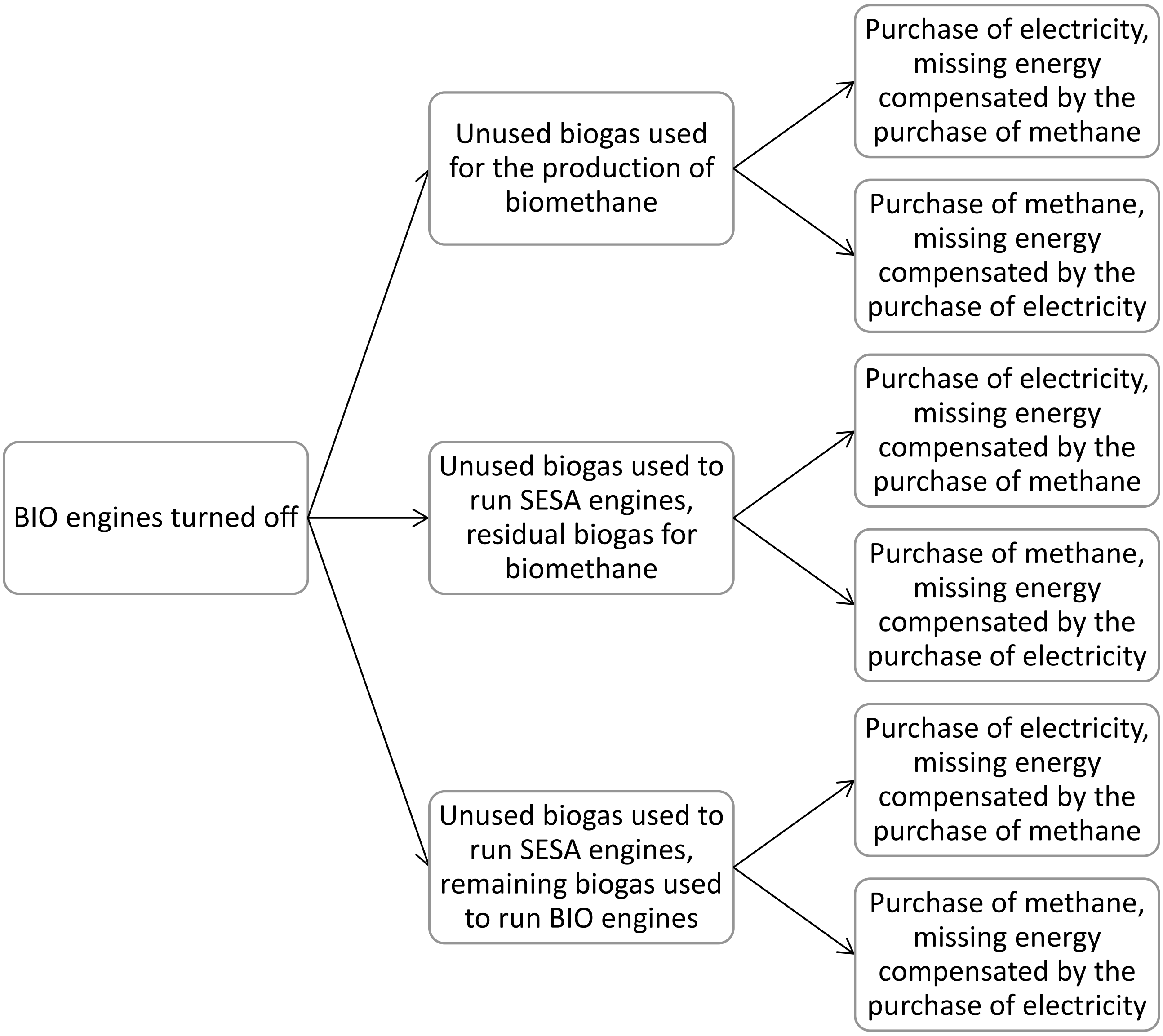

Figure 12: conceptual scheme of the case "BIO engines switched off".

Unused biogas used for the production of biomethane

In this situation it was assumed to keep the BIO engines switched off and then to use the unused biogas to increase the production of biomethane. Subsequently, as visible in the *Figure 13*, two subcases were analyzed:

- purchase of electricity, missing energy compensated with purchase of methane;
- purchase of methane, missing energy compensated with purchase of electricity.

With regard to the purchase of electricity and/or methane, the same considerations made above apply.

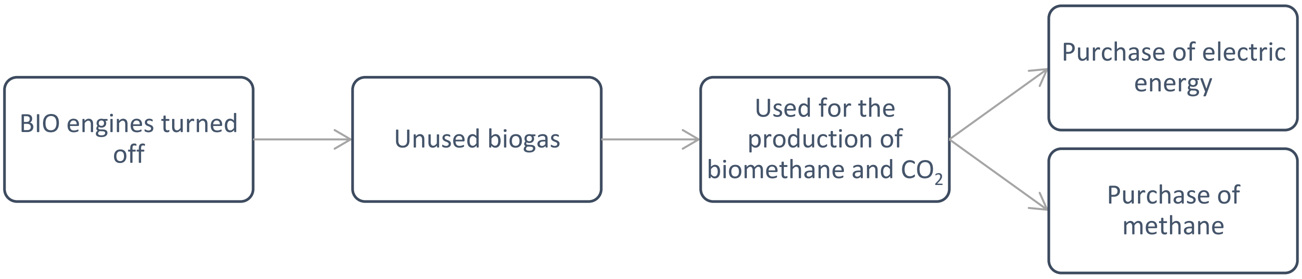

Figure 13: biogas for BIO engines shifted to biomethane production line.

Unused biogas used to run SESA engines, residual biogas in biomethane

Unlike the previous situation, in this case it is assumed that the amount of unused biogas following the shutdown of the BIO engines is used in the SESA engines, allowing them to work at a higher regime and generate more electricity to be self-consumed.

Since SESA engines can develop a maximum total power of 6972 kW, it is clear that they also have a maximum biogas consumption, which, on the basis of the initial conditions assumed, is equal to 3.002 Sm^3/h. Therefore, once the full power of SESA is reached, if biogas is still available, this, in this case, is used in the biomethane line to increase its production.

As in the previous case, the two sub-cases were also developed here:

- purchase of electricity, missing energy compensated with purchase of methane;
- purchase of methane, missing energy compensated with purchase of electricity.

to determine which energy carrier should be purchased.

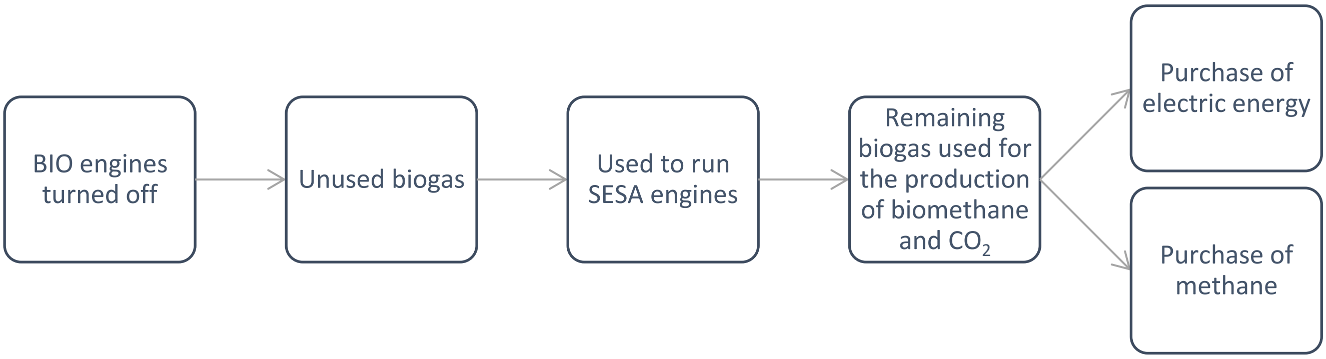

Figure 14: biogas for BIO engines shifted to SESA engines; remaining biogas used in biomethane production line.

Unused biogas used to power SESA engines, remaining biogas used to power BIO engines

This case is extremely similar to the previous one, with the difference that, while in the case seen above the remaining biogas following the achievement of the maximum power of the SESA engines was used by the biomethane line, here it is used to power the BIO engines.

With regard to the purchase of electricity and/or methane, the same considerations made above apply.

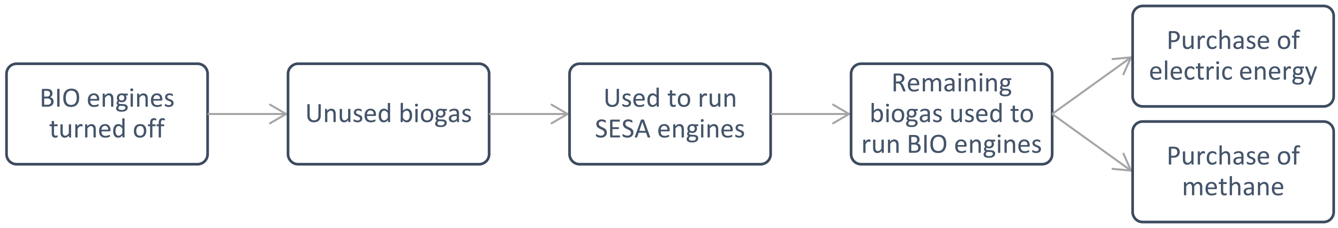

Figure 15: biogas for BIO engines shifted to SESA engines; remaining biogas used to run BIO engines.

7.5. Case "Minimum biomethane production"

In this third simulated case, it was assumed to produce the minimum quantity of biomethane to be sold through the SNAM network and to use the remaining biogas to power BIO and/or SESA engines. In particular, the case in which SESA engines are working at full capacity and BIOs are fed with the remaining biogas was analyzed; subsequently the case with BIO engines at full power and SESAs powered by the remaining biogas. The minimum quantity of biomethane to sold through SNAM network is 30.000 Sm^3/d, at which we must add the quantity required to run all the vehicles and that must be sold to S.E.S.A. partners, that is about 19.000 Sm^3/d.

In *Figure 16* the logical diagram.

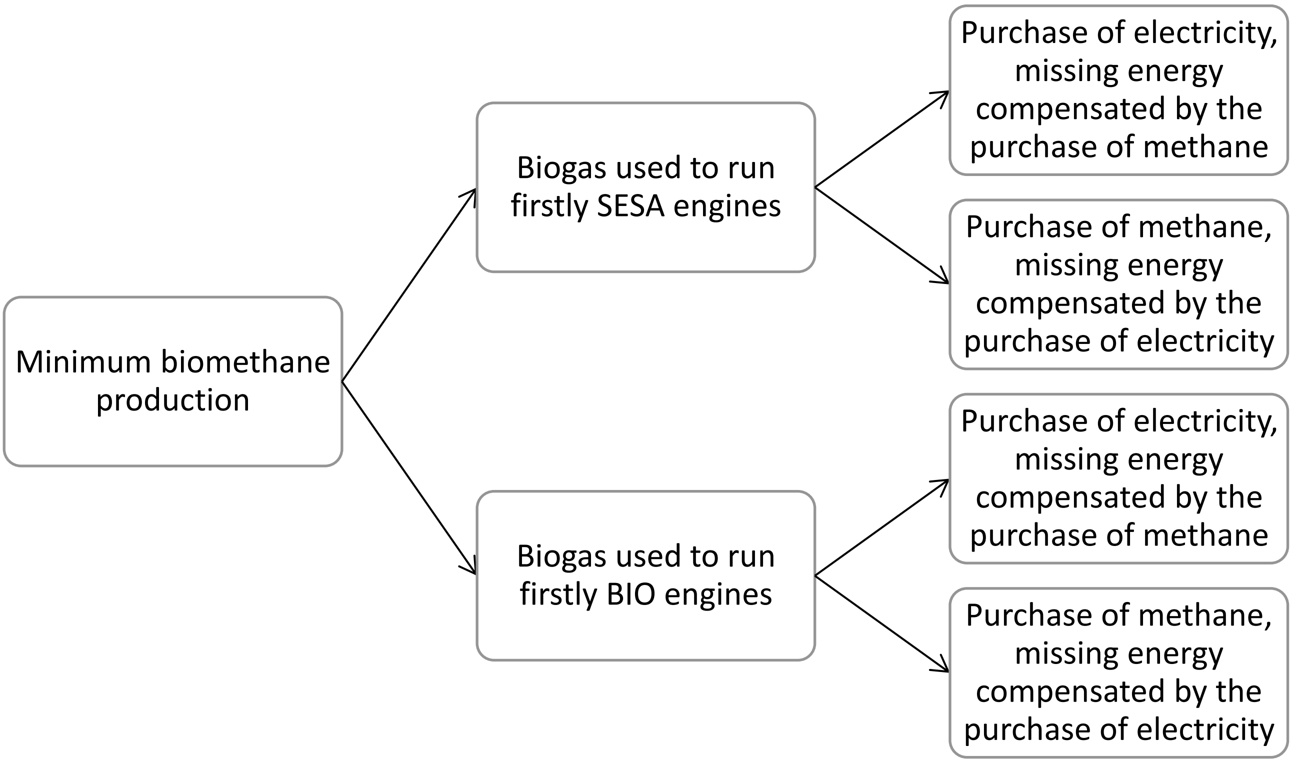

Figure 16: conceptual scheme of the case "Minimum biomethane production".

Minimum production of biomethane, remaining biogas used to power SESA engines

Assuming a minimum production of biomethane, it is clear that the amount of biogas available to power engines increases considerably. In the first sub-case it was decided to use this quantity first of all to power the SESA engines at the maximum possible power and, in the case of biogas was still available, also power the BIO engines.

Thus, the sequence becomes:

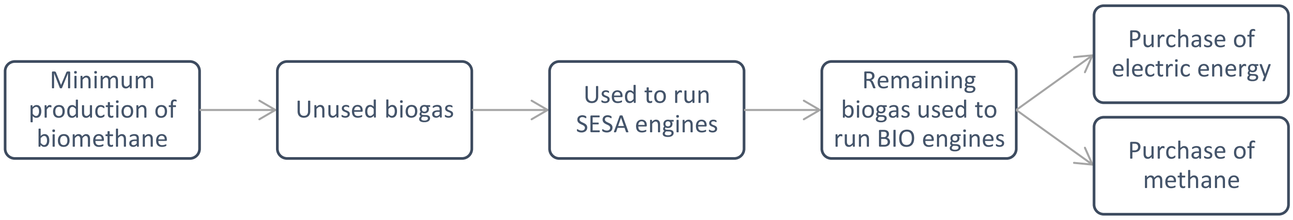

Figure 17: minimum biomethane production, remaining biogas used to run firstly SESA engines and, if some biogas is still available, to run BIO engines.

With regard to the purchase of electricity and/or methane, the same considerations made above apply.

Minimum production of biomethane, remaining biogas used to power BIO engines

In the second case, the engine supply sequence has only been reversed: now the BIO engines are powered firstly at the highest possible power and, if some biogas still be available, SESA engines are also powered. Here is the sequence:

Figure 18: minimum biomethane production, remaining biogas used to run firstly BIO engines and, if some biogas is still available, to run SESA engines.

With regard to the purchase of electricity and/or methane, the same considerations made above apply.

7.6. Case "Maximum production of biomethane"

In the fourth case under analysis it was decided that the main use of biogas is the production of biomethane, thus assuming that the production line always works at full capacity, equal to 4000 Sm^3/h. Subsequently, remaining biogas can be used in SESA engines or BIO engines. It is clear that maximum biomethane production implies also maximum CO_2 production. Below the logical scheme.

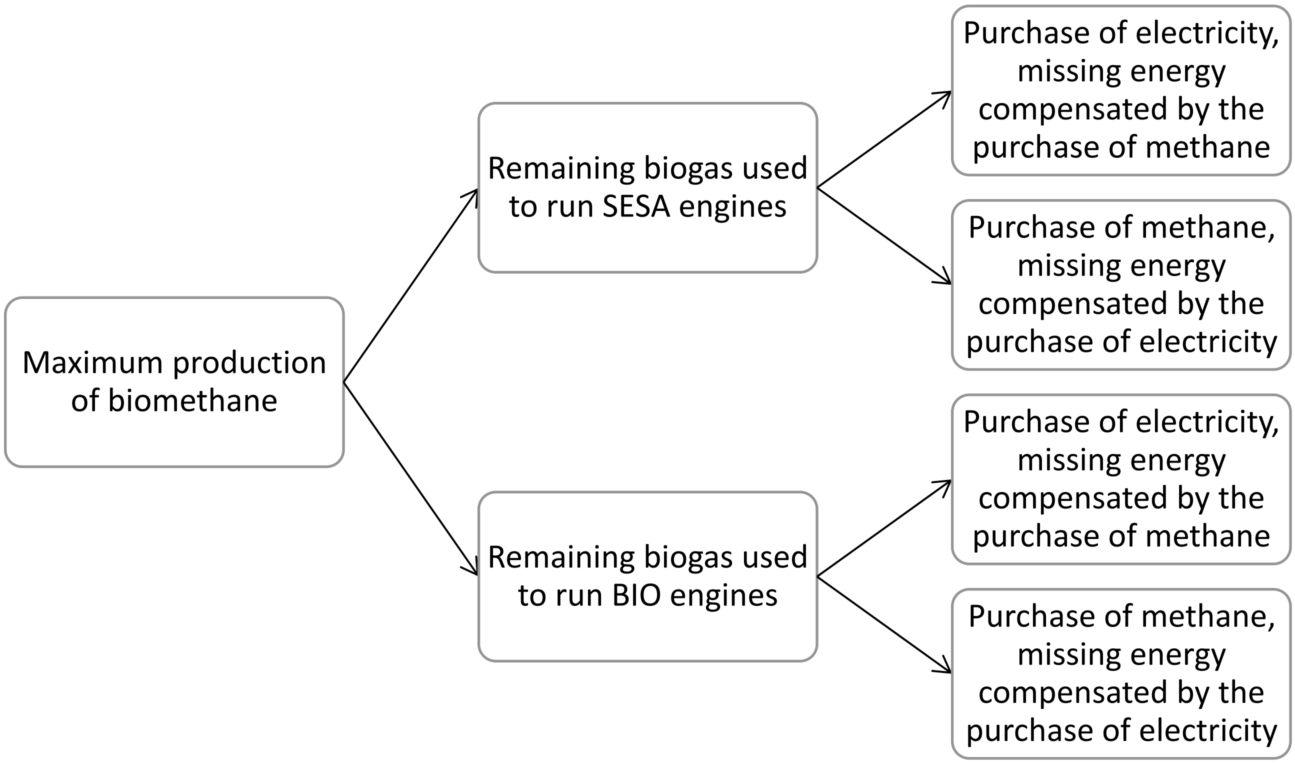

Figure 19: conceptual scheme of the case "Maximum production of biomethane"

The logic is the same as that applied in paragraph 7.5, with the only difference that before the biomethane line worked at minimum capacity, while now it works at maximum capacity. This implies that the amount of biogas to be used to power SESA and/or BIO engines decreases drastically compared to the previous case, consequently decreasing the power that can be generated by the engines but considerably increasing the amount of biomethane produced.

The two logical sequences are represented below.

Figure 20: maximum biomethane production, remaining biogas used to run firstly SESA engines and, if some biogas is still available, to run BIO engines.

Figure 21: maximum biomethane production, remaining biogas used to run firstly BIO engines and, if some biogas is still available, to run SESA engines.

7.7. Case "Maximum energy purchase"

In the last case analyzed, we reasoned differently: starting from the energy needs, it was decided, first of all, to buy all the possible energy or in the form of electricity, or in the form of methane and, only at this point, proceed assuming the maximum production of biomethane and running, with the remaining biogas, SESA or BIO engines. While, in the previous cases, we carried out calculations consuming firstly all the available biogas and only then we bought energy, in the situation under analysis firstly we buy the maximum amount of energy from the network (in the form of electricity or methane) and, subsequently, we proceed with the consumption of biogas: in this way, with the same energy needs, the amount of electricity that SESA engines must generate is lower, to the detriment of a greater amount of energy in purchase, as visible in *Figure 22*. As visible, in the case on the left the company buy less power from the grid but consume more biogas to produce electricity for self-consumption; on the right the company need to buy more power from the grid but need less biogas to produce electricity for self-consumption, increasing the amount of electricity to be sold thanks to the running of BIO engines.

Figure 22: comparative example between two different cases: on the left, maximum biomethane production, residual biogas used to run SESA engines and, in the end, purchase of electric power. On the right, maximum purchase of electric power and maximum biomethane production are assumed, then residual biogas used to run SESA engines and, after, used to run BIO engines.

Two main cases were distinguished: in the first, the maximum quantity of electricity from the network is purchased and, only if even after SESA engines are switched on energy is still needed, methane is also purchased; in the second case the opposite happens, therefore the maximum amount of methane is purchased to meet the energy needs and only if even after the possible run of SESA engines energy is still needed, electricity is purchased from the network.

Below, the logical schemes.

Figure 23: maximum purchase of electricity and maximum biomethane production; if some biogas is still available, it is used firstly to run SESA engines and then BIO engines.

Figure 24: maximum purchase of electricity and maximum biomethane production; if some biogas is still available, it is used firstly to run BIO engines and then SESA engines.

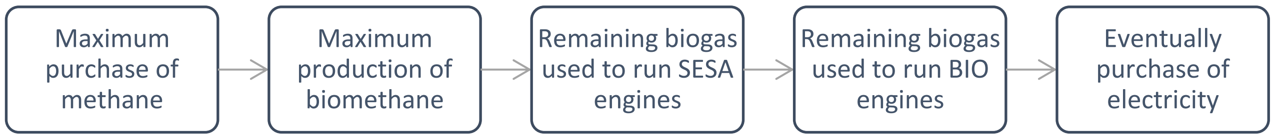

Figure 25: maximum purchase of methane and maximum biomethane production; if some biogas is still available, it is used firstly to run SESA engines and then BIO engines.

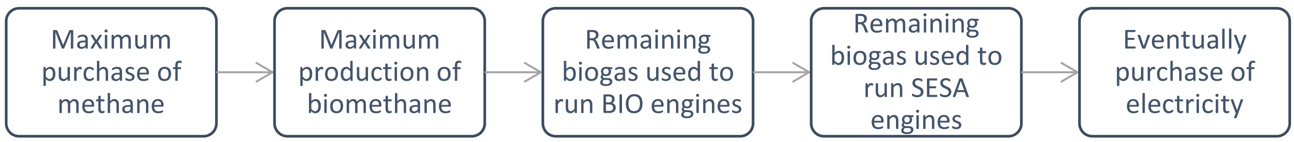

Figure 26: maximum purchase of methane and maximum biomethane production; if some biogas is still available, it is used firstly to run BIO engines and then SESA engines.

Finally, there is also a last case that considers a particular condition that could occur, consisting in buying the maximum amount of electricity from the network, compensating for the lack of energy with the use of SESA engines, using the remaining biogas for the production of biomethane and using any remaining biogas to power the BIO engines. Below is the logical scheme.

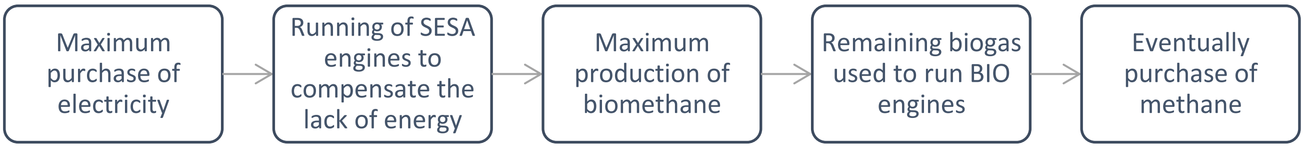

Figure 27: maximum purchase of electricity and running of SESA engines to satisfy the energy need. Remaining biogas used for production of biomethane; if some biogas is still available, it is used to run BIO engines.

8. Results

Tables below show the results of each month, highlighting the real operating conditions of that month and indicating what the company should have done to get the maximum profit. Since photovoltaic power consumed and sold is the same in the real situation and in the optimized one, these values are not reported in the following tables but they are considered in the calculations. The same for the engine BIO 5.

January

Initial condition:

Table 22: costs of energy, power needed and available biogas in January.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
224,500	86,909	0,297	1,032	6.645	5.083.546

Real situation:

Table 23: average operative conditions adopted by the company in January.

Gain	Operative conditions		
2.334.655 €	Average electric power purchased	788	kW
	SESA engines average power	3.338	kW
	BIO 6 average power	187	kW
	BIO engines average power	3.709	kW
	Ecomax average power	2.486	kW
	TLR2 average power	0	kW
	Biomethane production	1.496.905	Sm^3/month

Optimized situation:

Table 24: average operative conditions to obtain maximum gain in January.

Gain	Operative conditions		
3.072.830 €	Average electric power purchased	4.500	kW
	SESA engines average power	162	kW
	BIO engines average power	0	kW
	Ecomax average power	2.036	kW
	TLR2 average power	0	kW
	Biomethane production	2.976.000	Sm^3/month

February

Initial condition:

Table 25: costs of energy, power needed and available biogas in February.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
211,690	82,832	0,268	0,968	7.281	5.051.455

Real situation:

Table 26: average operative conditions adopted by the company in February.

Gain	Operative conditions		
2.469.996 €	Average electric power purchased	1.631	kW
	SESA engines average power	2.857	kW
	BIO 6 average power	239	kW
	BIO engines average power	3.740	kW
	Ecomax average power	2.619	kW
	TLR2 average power	0	kW
	Biomethane production	1.715.425	Sm^3/month

Optimized situation:

Table 27: average operative conditions to obtain maximum gain in February.

Gain	Operative conditions		
2.930.989 €	Average electric power purchased	4.500	kW
	SESA engines average power	0	kW
	BIO engines average power	1.689	kW
	Ecomax average power	2.830	kW
	TLR2 average power	0	kW
	Biomethane production	2.688.000	Sm^3/month

March

Initial condition:

Table 28: costs of energy, power needed and available biogas in March.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
308,070	128,317	0,347	1,443	7.128	4.723.665

Real situation:

Table 29: average operative conditions adopted by the company in March.

Gain	Operative conditions		
2.406.644 €	Average electric power purchased	1.938	kW
	SESA engines average power	2.057	kW
	BIO 6 average power	780	kW
	BIO engines average power	2.602	kW
	Ecomax average power	2.442	kW
	TLR2 average power	0	kW
	Biomethane production	1.819.642	Sm^3/month

Optimized situation:

Table 30: average operative conditions to obtain maximum gain in March.

Gain	Operative conditions		
3.368.658 €	Average electric power purchased	4500	kW
	SESA engines average power	0	kW
	BIO engines average power	0	kW
	Ecomax average power	2.649	kW
	TLR2 average power	0	kW
	Biomethane production	2.957.228	Sm^3/month

April

Initial condition:

Table 31: costs of energy, power needed and available biogas in April.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
245,970	104,154	0,178	1,171	6.818	3.861.193

Real situation:

Table 32: average operative conditions adopted by the company in April.

Gain	Operative conditions		
2.100.013 €	Average electric power purchased	3.398	kW
	SESA engines average power	778	kW
	BIO 6 average power	661	kW
	BIO engines average power	2.425	kW
	Ecomax average power	2.003	kW
	TLR2 average power	0	kW
	Biomethane production	1.649.979	Sm^3/month

Optimized situation:

Table 33: average operative conditions to obtain maximum gain in April.

Gain	Operative conditions		
2.716.376 €	Average electric power purchased	4.500	kW
	SESA engines average power	0	kW
	BIO engines average power	0	kW
	Ecomax average power	2.320	kW
	TLR2 average power	0	kW
	Biomethane production	2.432.019	Sm^3/month

May

Initial condition:

Table 34: costs of energy, power needed and available biogas in May.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
230,060	91,599	0,176	1,059	7.688	4.489.436

Real situation:

Table 35: average operative conditions adopted by the company in May.

Gain	Operative conditions		
2.709.369 €	Average electric power purchased	4.519	kW
	SESA engines average power	640	kW
	BIO 6 average power	596	kW
	BIO engines average power	626	kW
	Ecomax average power	1.926	kW
	TLR2 average power	0	kW
	Biomethane production	2.438.155	Sm^3/month

Optimized situation:

Table 36: average operative conditions to obtain maximum gain in May.

Gain	Operative conditions		
2.880.262 €	Average electric power purchased	4.500	kW
	SESA engines average power	234	kW
	BIO engines average power	0	kW
	Ecomax average power	3.000	kW
	TLR2 average power	0	kW
	Biomethane production	2.778.476	Sm^3/month

June

Initial condition:

Table 37: costs of energy, power needed and available biogas in June.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
271,310	105,152	0,178	1,219	7.756	4.237.054

Real situation:

Table 38: average operative conditions adopted by the company in June.

Gain	Operative conditions		
2.584.605 €	Average electric power purchased	4.594	kW
	SESA engines average power	1.913	kW
	BIO 6 average power	308	kW
	BIO engines average power	843	kW
	Ecomax average power	855	kW
	TLR2 average power	0	kW
	Biomethane production	2.039.947	Sm^3/month

Optimized situation:

Table 39: average operative conditions to obtain maximum gain in June.

Gain	Operative conditions		
2.839.815 €	Average electric power purchased	4500	kW
	SESA engines average power	307	kW
	BIO engines average power	0	kW
	Ecomax average power	3.000	kW
	TLR2 average power	0	kW
	Biomethane production	2.598.171	Sm^3/month

July

Initial condition:

Table 40: costs of energy, power needed and available biogas in July.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
441,650	174,692	0,184	2,180	8.013	4.510.674

Real situation:

Table 41: average operative conditions adopted by the company in July.

Gain	Operative conditions		
3.839.866 €	Average electric power purchased	3.887	kW
	SESA engines average power	2.296	kW
	BIO 6 average power	171	kW
	BIO engines average power	274	kW
	Ecomax average power	247	kW
	TLR2 average power	1.386	kW
	Biomethane production	2.244.590	Sm^3/month
	CO_2 production[4]	1.699	t/month

Optimized situation:

Table 42: average operative conditions to obtain maximum gain in July.

Gain	Operative conditions		
4.241.076 €	Average electric power purchased	4.500	kW
	SESA engines average power	0	kW
	BIO engines average power	0	kW
	Ecomax average power	0	kW
	TLR2 average power	3.556	kW
	Biomethane production	2.817.948	Sm^3/month
	CO_2 production	2.133	t/month

[4] CO_2 production and revenues are considered only starting from July because in this month the company has started a second line for CO_2 recovery with higher productivity compared with the first line, increasing the quantity available, and because before July price of CO_2 was considerably lower, generating a negligible gain for the purpose of the analysis.

August

Initial condition:

Table 43: costs of energy, power needed and available biogas in August.

PUN (€/MWh)	PSV (€/MWh)	Electricity cost (€/kWh)	Methane cost (€/Sm^3)	Average power required by the plant (kW)	Biogas produced (Sm^3)
543,150	232,658	0,227	2,9048	8.366	5.275.749

Real situation:

Table 44: average operative conditions adopted by the company in August.

Gain	Operative conditions		
6.098.909 €	Average electric power purchased	4.434	kW
	SESA engines average power	2.521	kW
	BIO 6 average power	265	kW
	BIO engines average power	17	kW
	Ecomax average power	881	kW
	TLR2 average power	536	kW
	Biomethane production	2.724.606	Sm^3/month
	CO_2 production	1.949	t/month

Optimized situation:

Table 45: average operative conditions to obtain maximum gain in August.

Gain	Operative conditions		
6.300.386 €	Average electric power purchased	4.500	kW
	SESA engines average power	1.602	kW
	BIO engines average power	0	kW
	Ecomax average power	2.430	kW
	TLR2 average power	0	kW
	Biomethane production	2.976.000	Sm^3/month
	CO_2 production	2.130	t/month

Of course, the sum of the power consumed does not correspond perfectly to the power demand: this is due mainly to energy losses and, sometimes, energy meters malfunctions. Anyway, the error is negligible.

Taking up from the initial question of the study on what was the best energy carrier to use and what was the best use of biogas, following the analysis conducted it was possible to give a clear answer: for the company in the months under analysis was better to buy electricity to meet energy needs, and produce as much biomethane as possible. Therefore, making an operational analysis, the ideal sequence to optimize the plant was: produce as much biomethane as possible, use the remaining biogas to power the SESA group engines, buy the remaining amount electricity from the grid and, if necessary, use methane engines to produce electricity to be consumed. Only in February there is a difference: in fact, being the month with the lowest PSV, in this case it would have been better for the company to use the remaining biogas to power BIO engines instead of SESAs and, consequently, buy more energy from the grid.

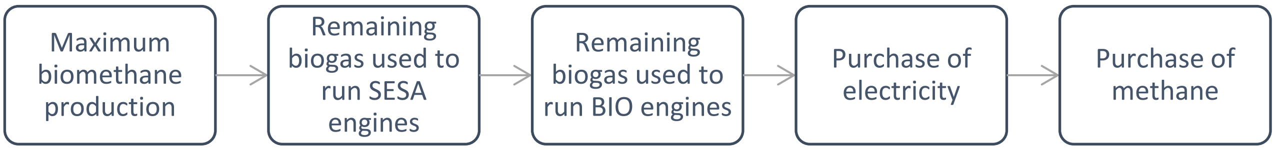

Figure 28: optimal operating conditions to achieve maximum gain. It is valid for all months, except for February.

Making the ratio between the gain of the real situation and the gain of the optimized situation you get an average value of 77% for the period from January to April, and equal to about 92% in the months from May to August.

8.1. Considerations

Looking at the results obtained from the analysis, even if the obtained results are good (never less than 70% of efficiency), it can be immediately noted that in the period from January to April the margin of economic improvement in percentage is more than in other months, but before arriving at hasty conclusions it is good to contextualize the result. As mentioned at the beginning of the study, in fact, thermal energy was not considered in carrying out this analysis; it is important to remember that biodigesters require thermal energy to work (and thermal energy is also needed by the district heating network), thermal energy that is provided by the heat recovered because of the use of SESA, BIO and methane engines. Therefore, it is necessary for the plant management to turn on engines, because, being able to recover the thermal energy of these, the company does not need to buy more energy from the network, thus reducing costs and, above all, environmental impacts and reaching a decidedly higher level of sustainability. In fact, if that thermal energy was not recovered, it would simply be dispersed. Anyway, a thermal energy analysis must be done to quantify how much heat is necessary for the plant and for the district heating network. In this way, it is possible to identify precisely how many engines need to be turned on to satisfy thermal and electrical demand at the same time.

Another important factor to consider evaluating the results is that the study assumes that the plant, as a whole, always works. The reality, however, is that all this system of biodigesters, biomethane production lines, biogas engines, methane engines and everything in the plant needs periodic maintenance (with a consequence stop of the section under maintenance) and can suffer breakages during the production process. As a result, sometimes operators are in situation in which it is impossible to make choices to optimize the production process and therefore some decisions are forced. If, for example, in a particular period, for the company was convenient to produce biomethane but the biomethane line was not working, the forced choice was to turn on the SESA and BIO engines to burn biogas and produce electricity since the biogas produced must necessarily be used having no possibility of being stored.

8.2. From an historical assessment to a forecasting model

Following the analysis conducted, starting from the data collected and the spreadsheets used, we began to develop a software that will then be able to collect site data, PSV and PUN values continuously independently, with the objective to develop, at the end, a PLC. By connecting this software with the operators' PCs and smartphones, it will allow them to check in real time if the plant, in its entirety, is operating at optimal conditions or if changes are necessary. At the moment the program is in its initial stage, but a "basic" version developed on Excel already allows operators to make more targeted choices every day. The system, actually, is not fully automated and does not take into account any breakages and/or problems that may occur. In any case, it is still efficient as by entering the value of the PSV displayed in the "Gestore Mercati Energetici" portal and the quantity of biowaste entering the plant, it is able to establish which are the best operating conditions on the i-day. It will then be up to the operator to establish what is possible to do to obtain maximum performance based on the real status of the plant. The future goal is that the software will be able to suggest the best operating conditions based on the real state of the plant, so considering also breakages and maintenance.

Averagely, in the first weeks of November of use of the software, it has been seen that it is better to use biogas for the maximum possible production of biomethane and buy electricity. Regarding the running of BIO engines or SESA engines, it depends mainly on the PSV. In general, the lower the PSV, the more convenient it is to use BIO engines; the higher the PSV, the more convenient it is to use SESA engines. Concerning the running of ECOMAX and TLR2, if the sum of power purchased from the grid and power generated by SESAs is not enough, at least one of the two methane-engine is necessarily turned on to compensate for the missing power.

In any case, what is important is that the software allows S.E.S.A. to make a truthful daily forecast of optimal conditions, allowing the company to improve its efficiency and the monitoring of the plant.

8.3. About environmental impacts

Following the survey carried out, an impact analysis was also made to compare the emissions in terms of CO_2 equivalent generated by the company for energy consumption with the emissions of the optimized case.

For CO_2 emissions factor due to the use of electricity purchased from the network, a coefficient of 0,246 kg CO_2 eq/kWh is used. (Caputo, A., 2022)

With regard to the ECOMAX and TLR2 methane engines, an emission factor of 0,315 kg CO_2 eq/kWh has been assumed for the joint production of electricity and heat. (Caputo, A., 2022)

Instead, in accordance with ISPRA, the CO_2 emission factor from biogas combustion is considered zero. In this context, biomass is a neutral source with respect to CO_2 emissions, as the CO_2 emitted during combustion is equal to that absorbed during the life of the plant with the process of photosynthesis. (Caputo, A., 2022)

Given these premises, the following table shows the month-by-month comparison between the emissions of the real operating condition and the hypothetical optimized one.

Table 46: S.E.S.A. greenhouse gas emissions in terms of CO_2 eq., considering only consumption (and not avoided emission).

Month	Real operating conditions	Optimized operating conditions
January	727.602 kg CO_2 eq	1.301.328 kg CO_2 eq
February	824.639 kg CO_2 eq	1.343.798 kg CO_2 eq
March	927.681 kg CO_2 eq	1.445.100 kg CO_2 eq
April	1.056.748 kg CO_2 eq	1.323.907 kg CO_2 eq
May	1.279.052 kg CO_2 eq	1.527.542 kg CO_2 eq
June	1.007.788 kg CO_2 eq	1.478.304 kg CO_2 eq
July	1.094.769 kg CO_2 eq	1.527.581 kg CO_2 eq
August	1.143.963 kg CO_2 eq	1.393.868 kg CO_2 eq

The result obtained is not surprising and is a predictable result: the cogeneration engines of the SESA group produce electricity whose CO_2 emitted is considered biogenic since the biogas comes from biomass. Therefore, the share of energy to be purchased, whether in the form of methane or electricity, decreases, decreasing in turn the impacts generated.

However, it is necessary to make a consideration: in the optimized situation, the quantity of biogas that is not used to power SESA engines is used for the production of biomethane and CO_2, also coming from biomass processing and, therefore, considered sustainable in terms of environmental impact. In fact, the results reported in *Table 46*, report the emissions in terms of CO_2 equivalent only for energy consumption, but does not consider the amount of CO_2 sequestered as a result of the entire process. The company periodically carries out global surveys on CO_2 equivalent emissions and the result obtained is that the emissions generated by S.E.S.A., in its entirety, are negative and equal to -77.000 t/year.

A further analysis carried out is a comparison between energy consumed by the site with that produced. As the data show, in fact, the company consumes a large amount of energy for waste processing; however, following the valorization of waste, it also produces renewable energy, both in the form of electricity and methane. The table below shows the total amount of energy consumed by the company month by month and the amount of total energy produced.

Table 47: comparison between consumed energy and produced energy by the company.

Month	Consumed energy (kWh)	Produced energy (kWh)	P-C (kWh)	$\frac{Consumed}{Produced}$
January	10.291.778	17.480.645	7.188.867	58,9%
February	9.766.125	19.228.567	9.462.442	50,8%
March	9.897.025	19.121.309	9.224.284	51,8%
April	8.517.143	17.290.129	8.772.987	49,3%
May	9.462.630	23.383.102	13.920.472	40,5%
June	7.391.689	19.861.244	12.469.556	37,2%
July	9.093.829	21.417.043	12.323.214	42,5%
August	8.054.991	25.832.726	17.777.735	31,2%

From the results obtained it can be seen that the energy consumed by the company is on average 45% compared to that produced. Moreover, the result obtained assumes an even more importance if we consider that all the energy produced comes from renewable sources.

9. Conclusion

The analysis conducted allowed, starting from historical data, to identify the margins for improvement of the company and to study what operations to do to optimize the process. Starting from the historical analysis, it has then allowed to start the development of forecasting software that is already allowing the company to obtain important improvements, especially from an economic point of view. Anyway, results demonstrated that the company is operating in the correct direction as regards energy optimization, obtaining a real situation/optimized situation gain ratio always above 70%, even reaching values above 90%, demonstrating that has control over the energy situation.

As expected, thermal energy analysis is necessary to have a complete overview. In the next months, it will certainly be carried out, but for now the study carried out is already of great help to have a quantifiable result and to develop a very precise forecast model.

Moreover, thanks to the creation of the company's energy profile, it has been seen that although the company's energy consumption is high, the amount of energy produced and sold in the form of electricity and biomethane is much higher than that consumed by the company. It must also be remembered that all the energy produced by the company comes from renewable sources, an extremely important result from the point of view of environmental impacts and which shows how the company has been projected into the future. To confirm this there is also the result of the analysis carried out in the CIC portal: currently the company's emissions in terms of ton CO_2 are negative and are decreasing year after year, going from -55.000 t of last year to the current -77.000 t.

I conclude by stating that the survey carried out has not only allowed an optimization and better monitoring from the energy point of view with a consequent increase in profit but has also allowed to confirm the attention to the environment and the environmental sustainability of the company itself, demonstrating how economic efficiency and environmental efficiency can have a meeting point and go hand in hand, allowing very high-performance levels.

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