PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Dynamic Analysis Of A Power Plant Producing Liquefied Biomethane For Heavy Road Transport

Francesco Calise[a], Francesco Liberato Cappiello[b], Luca Cimmino[c] and Maria Vicidomini[d]

[a] *Univesità degli studi "Federico II", Napoli (NA), Italy, frcalise@unina.it*
[b] *Univesità degli studi "Federico II", Napoli (NA), Italy, francescoliberato.cappiello@unina.it*
[c] *Univesità degli studi "Federico II", Napoli (NA), Italy, luca.cimmino@unina.it, CA*
[d] *Univesità degli studi "Federico II", Napoli (NA), Italy, maria.vicidomini@unina.it*

Abstract:

In the recent years, European Countries are paying more and more attention to the issue of greenhouse gases emissions due to the road transport sector. In particular, the fuel consumption due to the heavy road transport is one of the most relevant issues both for the weight and the long distances that they cover. In addition, the cost of the natural gas dramatically increased in many European countries due to recent international crisis. Thus, finding alternative ways of producing natural gas from renewable sources would be of great economic and environmental impact for the current global asset. In this work, a dynamic thermoeconomic analysis of a plant producing bio liquefied natural gas (bio-LNG), driven by renewable sources, to meet the fuel demand of a fleet of heavy trucks is proposed. The plant consists of a plug flow reactor digesting the organic fraction of municipal solid wastes in mesophilic conditions. The biogas upgrading model and the biomethane liquefaction models are in detail developed in MATLAB. The whole system is integrated in TRNSYS for dynamic simulation purpose. Then, the bio-LNG is used to meet the fuel demand of heavy trucks which cover relevant distances all over the region of Campania, in the South of Italy. The environmental impact related to the avoided emissions due to the use of bio-LNG is analysed together with the economic feasibility of the proposed system. The results of the thermoeconomic simulation show that the system has high capital costs, close to 85 M€ despite the fundings granted for bioLNG trucks purchasing. However, the fundings for the biomethane production and selling are enough to guarantee a remarkable economic feasibility with a Simple Payback period of less than 2 years and a Net Present Value of 402 M€. Furthermore, the solution proposed is effective for the pathway of the green mobility, with a Primary Energy Saving of 91% and a reduction of CO_2 emissions by 86%.

Keywords:

Liquefied biomethane; plug flow reactor; renewable energy; heavy-duty truck; Linde cycle.

1. Introduction

To achieve the goal of the climate neutrality by 2050, the European Commission of the European Union (EU) issued several directives that must be mandatorily attended by all the EU Countries [1]. To this scope, a first key set of proposals to revise EU Legislation was signed in 2021, known as "fit for 55" package [2]. The main purpose of this package is to reduce by 55% CO_2 emissions by the end of year 2030, compared to the year 1990. The proposals include a significant revision in EU policies on energy taxation, carbon border adjustment mechanisms and emissions trading systems. In this framework, particular attention was paid to the transport sector, which is still responsible for over 25% of greenhouse gases (GHG) emissions, by including a strict alternative fuels infrastructure regulation [3]. Nowadays, there are 13.4 million of alternative fuel road vehicles in the EU, around 5% of the total number, but estimations predict an exponential increasing trend of alternative fuels spreading in the next 20 years [4]. More specifically, large attention is paid to the installation of alternative refuelling points on the main roads, to allow vehicles, especially heavy-duty trucks, to circulate throughout the EU countries [5].

The environmental impact of the heavy-duty trucks is indeed widely acknowledged and the main reason lies behind the ever increasing spreading of worldwide freight shipments [6]. The current globalized market allows the trade of products among the most remote parts of the world by means of containers which carry out tons of consumer goods. These goods are then overwhelmingly land transported by heavy trucks for internal moving among the ports of the same country [7]. Unfortunately, the sustainability of this market is jeopardized by the increasing connections of ports for the exchange of containers, that comes with the increase of the number of

 https://doi.org/10.52202/069564-0157

heavy-duty trucks for road transport of containers. In this framework, among the proposals for the EU Legislation revision for a sustainable development, the installation of alternative fuels refuelling stations in the busiest seaports was indeed considered [8]. This strategy mainly involves electric batteries recharging, but the usage of liquefied natural gas (LNG) is also taken into account. Unfortunately, latest directives in terms of road transport vehicles circulation are aiming to the utter replacement of internal combustion engine vehicles with electric vehicles by 2035 []. However, these directives are still under discussion since several EU Countries are concerned that this pathway is not at all the most efficient and sustainable for the road to the full decarbonisation. In fact, cutting-edge solutions for the progress towards a green mobility not only include electric road transport [9], but also hydrogen vehicles [10] and vehicles fuelled with compressed natural gas (CNG) and liquefied natural gas (LNG), even produced starting from biomass, respectively named bio-CNG and bio-LNG. In fact, the scientific literature shows an increasing number of studies involving produced emission analyses and economic feasibility of these solutions compared to Diesel fuelled heavy trucks [11]. A case study with real drive cycles was conducted in British Columbia [12] and it was estimated that CNG trucks emit 15% less CO_2 than Diesel trucks, primarily depending on drivetrain technology rather than operating conditions. The same results is found in similar works [13].

However, what is mostly catching the eye nowadays is the possibility of exploiting the biomasses to produce fuels that are utterly eco-friendly [14]. In fact, electric road transport is a solution which is still not sustainable as a unique for the advancement towards the "green mobility" and alternative solutions are increasingly pursued. This, in particular, is shown by the ever and ever growing interest for the study of power-to-fuels (PtF) technologies [15]. The anaerobic digestion (AD) process for the production of biogas from the municipal wastes is a well-known technology and it is suited for PtF systems. In fact, it allows one to combine the urban waste recycling and the necessity of producing natural gas from renewable sources. The biogas produced by the AD is a gaseous compound mainly consisting of methane (CH_4) and carbon dioxide (CO_2), with other minor impurities [16]. After a process of clean up, required for the poisoning components included in the biogas, this gas may undergo an upgrading process to separate, with a high grade of purity, the CH_4 from the CO_2 [17].

On the one hand, the most commonly adopted solution for the biogas upgrading is the membrane separation process [18]. This solution provides biomethane with a still significant gas purity (around 95%) and is the less expensive, so it is vastly adopted for the production of CNG. On the other hand, the biogas upgrading process with the highest percentage purity of the final biomethane obtained as by-product is the liquefaction [19]. The LNG is mainly obtained by means of the cryogenic separation process. However, this process is high-energy demanding since the biogas must be compressed up to 20 MPa and cooled down to -161°C [20]. Naquash et al. [21] provided an energy and exergy analysis of the biomethane liquefaction process with mixed-refrigerant followed by CO_2 solidification. The process simulated in Aspen and validated with experimental data showed a 68.6% of energy saving with respect to the case in absence of CO_2 solidification. Furthermore, a beneficial specific consumption of 0.49 kWh/kg was observed with respect to the base case where 1.57 kWh/kg were required. The greatest exergy rate is due to the cryogenic heat exchangers. In [22] the authors compare two different upgrading options, namely cryogenic separation and ammine absorption, combined with liquefaction for LNG production. Models were simulated in Aspen and optimized for minimization of energy consumption. In case of cryogenic upgrading, the specific consumption resulted of 2.07 kWh/kg whereas for ammine absorption, a value of 3.35 kWh/kg was obtained, also considering the heat required for regenerating the ammines. In reference [23], a comparative energy, environmental and economic analysis is proposed for the biogas upgrading and distribution of CNG and LNG. As a result of the analysis, it was obtained that differences among different biogas upgrading and biomethane liquefaction technologies, using a life cycle analysis, are marginal, especially in case of long-distance transportation of the gas. However, the longer the distance to the customer, the more convenient the bio-LNG with respect to the bio-CNG.

The aim and novelty of the work here proposed can be summarized in the following points:

- Development of an innovative layout based on a plug flow reactor fed by organic fraction of municipal solid waste for the production of biogas, equipped with biogas upgrading unit and biomethane liquefaction unit
- Adoption of a solar PV system with lithium-ion battery for analysis of the specific energy consumption for the production of the bio-LNG
- Thermoeconomic analysis of the model in dynamic operating conditions with specific case study for meeting the fuel demand of a fleet of heavy-duty trucks

2. Layout

The layout of the system is shown in figure 1.

In the proposed system configuration, the whole liquefied biomethane production is based on the anaerobic digestion (AD) of the organic fraction of municipal solid wastes (OFMSW) within a plug flow reactor (PFR). The PFR is fed by the biomass, converted in biogas by the AD process. The biogas production is almost constant in rated operating conditions and a buffer is equipped downstream the PFR to ensure constant operating

https://doi.org/10.52202/069564-0157

conditions of the biogas upgrading unit [24]. The thermal demand of the digester is partially met by evacuated tube solar collectors (ETC), the integration occurs by means of a biomass-fed auxiliary boiler.

The biogas upgrading unit is a hollow fiber three-stage membrane compression system which separates the methane from the carbon dioxide. The three-stage compression is intercooled by means of sea water heat exchangers, so the inlet temperature from the cold side continuously changes. Thus, the energy consumption of the process is not constant despite the constant operating flow rate of biogas. The biomethane obtained as a by-product from the separation of the carbon dioxide is supplied to the liquefaction unit, operating according to the Linde industrial process [25]. Details of the models are discussed in the following section. Here only the final result of the process is explained. In fact, the biomethane is cooled down to the saturation temperature at ambient pressure and the liquid phase is separated from the steam phase. The former one is captured and sold as LNG, the latter is instead used to refill the process and repeat the cycle. The precooling of the biomethane is realized by means of an ammonia electric chiller, then a lamination valve realizes the final cooling. This whole cycle of biomethane production and liquefaction is also equipped with a PV system and a Lithium-Ion battery (LIB). This equipment is considered to partially meet the energy demand of the process and increase the share of renewables in the overall bio-LNG production. The PV system coupled with the LIB is responsible for meeting the load of the upgrading unit and the liquefaction unit, together with the auxiliary electricity-driven devices.

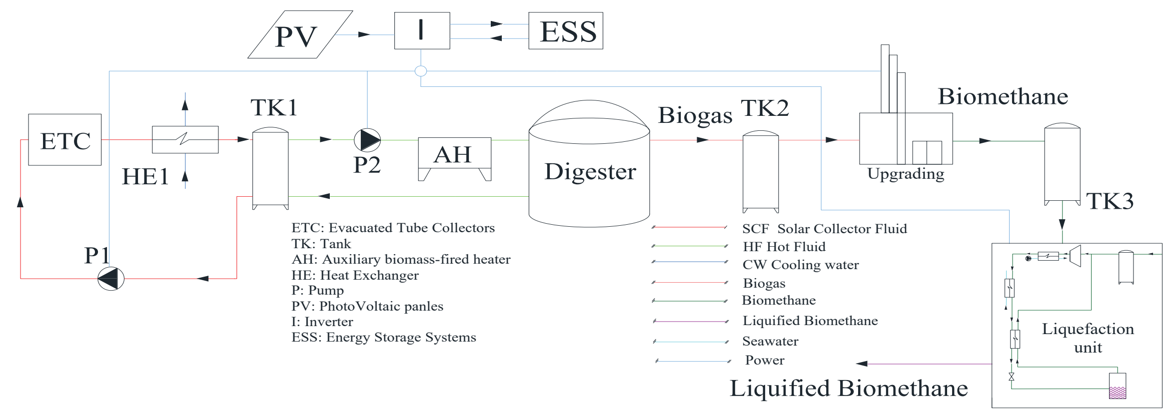

Figure. 1. Layout of the plant.

3. Model

In this section the main models developed by the authors are shown and discussed. The models are first developed in MatLab and then integrated in TRNSYS environment to perform the dynamic simulation of the plant including all the technologies proposed. Furthermore, the thermoeconomic model adopted to perform the energy, environmental and feasibility analysis of the solution proposed is shown. The following models are proposed by the authors and discussed in this work:

- Plug Flow reactor for the biogas production
- Membrane separation for the biogas upgrading
- Biomethane liquefaction

3.1. Plug Flow reactor

The plug flow reactor (PFR) model here developed is based on the discretization of the system of partial differential equations for the anaerobic digestion and the heat transfer phenomena occurring in the reactor. The model has been widely explained by the authors in previous works [26], together with its validation. The biological model is based on the anaerobic digestion model n.1 (ADM1) with some simplified assumptions on the number of species taking part to the process, eq.(1) [26]. The thermal model is instead based on the well-known heat transfer equation for heat exchangers, eq.(2) [27]. In addition, the thermal balance between the digester and the environment is considered, see eq.(3) to understand how dynamically varies the thermal demand basing on the heat loss to the ambient. The main equations involved in the model are thus the following:

$$\frac{dC_{w,i}}{dt}=\frac{\dot{V}_{w,in}}{V_w}\left(C_{w,i,in}-C_{w,i}\right)+\sum_j \rho_j \nu_{i,j} \tag{1}$$

https://doi.org/10.52202/069564-0157

$$\dot{m}_{wat} C_{p,wat} \left(T_{in,wat} - T_{out,wat} \right) = n U_{HE,n} A_{HE,n} (\bar{T}_{in,wat} - \bar{T}_{react}) \tag{2}$$

$$\dot{m}_{OFMSW} C_{p,OFMSW} T_{in,OFMSW} + \dot{m}_{wat} C_{p,wat} \left(T_{in,wat} - T_{out,wat} \right) - \dot{m}_{dig} C_{p,dig} T_{react} + \\ - \dot{m}_{biogas} C_{p,biogas} T_{react} - \dot{Q}_{loss} = \rho_{OFMSW} V_{OFMSW} C_{p,OFMSW} \frac{dT_{react}}{d\vartheta} \tag{3}$$

Where $C_{w,i}$ is the concentration of the bacterial species considered, $V_{w,in}$ is the input waste volumetric flow rate, V_w is the volume occupied by the biomass in the digester, $C_{w,i,in}$ is the concentration of the i-th species in the input flow rate. The last term is the sum on the j-th process of all the kinetics terms times the reaction coefficient of the i-th biochemical species involved in the j-th process. The temperature at which the kinetic terms of the biological process are iteratively calculated according to the thermal balance on the digester and the heat exchange with the inner water heat exchanger.

3.2. Membrane separation

The biogas upgrading process is based on a three-stage hollow fiber membrane compression unit in which each stage includes a double stage compression with inter-refrigeration by means of seawater heat exchangers, see figure 2.

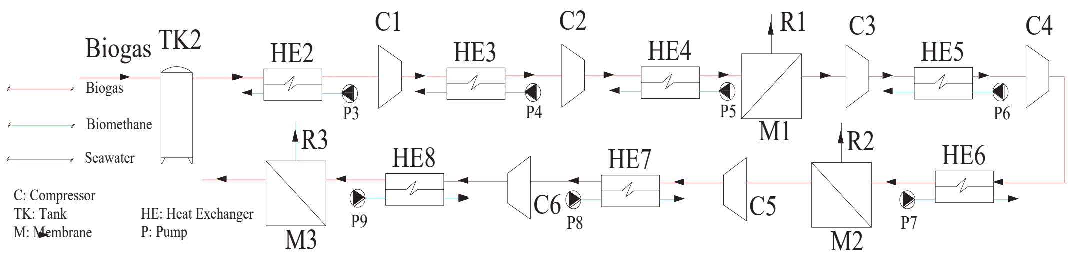

Figure. 2. Membrane separation unit.

The gaseous compound compressed is sent to the membrane at the end of each stage and the different permeability of CH_4 and CO_2 at a given operating pressure and temperature drive the separation process. In fact, due to the different permeability of the gases, two different streams are obtained, one rich in CH_4 (retentate) and one rich in CO_2 (permeate) [28]. The detailed model of the system of equations describing the process is discussed in [29].

3.3. Biomethane liquefaction

The biomethane obtained from the biogas upgrading process is the liquefied by means of a Linde cycle where the biomethane itself is the working fluid, see figure 3.

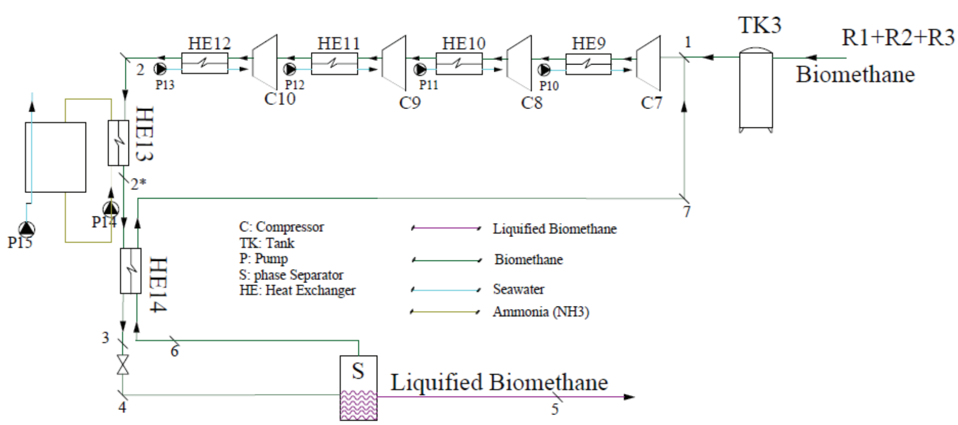

Figure. 3. Biomethane liquefaction unit.

The biomethane first undergoes an inter-refrigerated multi-stage compression up to the rated operating pressure of the cycle of 20 MPa. Here, the temperature is still the ambient temperature, T = 25°C. Then, the biomethane is cooled down to the temperature of -50°C through the evaporator of an ammonia electric chiller.

https://doi.org/10.52202/069564-0157

This heat exchanger HE13 is pivotal to drive the operation of the cycle in the transient conditions, since after this precooling the biomethane is furtherly cooled down by means of the regenerative heat exchanger HE14. After this, a throttling valve is used to decrease the pressure of the biomethane down to the ambient pressure and obtained saturated steam. The liquid fraction of the biomethane is spilled and stored, whereas the steam is used as cold fluid for the HE14 and then as a refill for the cycle. The model is developed in MatLab and iteratively calculates the variables T_3, T_7 and x_4 by means of the following system:

$$\begin{cases} h_4 = h_6 x_4 + h_5 \cdot (1 - x_4) \\ \dot{Q}_{HE14} = \dot{m} \cdot x_4 \cdot (h_7 \cdot - \cdot h_6) \\ \dot{Q}_{HE14} = \dot{m} \cdot (h_{2^*} \cdot - \cdot h_3) \end{cases} \tag{4}$$

Where Q is the heat transfer rate and h is the enthalpy of a specific state point.

There is no direct validation of these models against experimental data but each of them is based on well-known and globally accepted equations for the calculation of the biogas production, the membrane separation, and the Linde cycle. Therefore, the model as a whole can be considered intrinsically valid, since all the results are also consistent with data available from literature.

3.4. Thermoeconomic model

The thermoeconomic analysis is based on a widely adopted approach which allows to evaluate the energy, environmental, and economic performance of the proposed system (PS) with respect to the reference system (RS) by means of few key performance indicators [30]. The RS in this case is the one including the heavy-duty trucks equipped with Diesel engines, with the fuel provided by the GPL stations. In the PS, the heavy-duty trucks are equipped with LNG engines whose fuel demand is partially met by the renewable plant described. The Primary Energy Saving (PES) is calculated as $\Delta PE/PE_{,RS}$ where ΔPE is:

$$\Delta PE = PE_{RS} - PE_{PS} = \left(M_{Diesel} LHV_{Diesel}\right)_{RS} - \left[\frac{E_{el,fromGRID} - E_{el,toGRID}}{\eta_{el,grid}}\right]_{PS} \tag{5}$$

Where $\eta_{el,grid}$ is the efficiency of the national electric grid, $M_{LNG,dem}$ is the fuel demand of the heavy-duty trucks adopting LNG engines and $M_{LNG,prod}$ is the LNG produced by the renewable plant proposed. The CO_2 emissions saved are calculated according to the emissions factors of electricity and diesel consumed [31]:

$$\Delta CO_2 = CO_{2,RS} - CO_{2,PS} = \delta_{trucks} f_{trucks,D} - \left(E_{el,fromGRID} - E_{el,toGRID}\right) f_{EE} \tag{6}$$

Where δ_{trucks} is the total distance covered by the heavy-duty trucks and $f_{trucks,D}$ is the CO_2 equivalent emission factor for Diesel fuel trucks [31].

The economic feasibility is instead evaluated by means of the cost savings due to the PS:

$$\begin{aligned} \Delta C &= C_{RS} - C_{PS} \\ &= (V_{Diesel} c_{u,Diesel})_{RS} - (E_{el,fromGRID} c_{u,EE} + M_{wc} c_{wc} + E_{el,toGRID} p_{u,EE} - CIC + M)_{PS} \end{aligned} \tag{7}$$

Where the term M represents the maintenance costs whereas CIC is referred to the fundings granted by the Italian Government for the production of biomethane from municipal organic wastes [24]. More precisely, for the calculation of the operative costs for both the RS and the PS, the carbon tax for the CO_2 emissions due to fossil fuels consumption is considered [32].

The capital cost of the system includes the cost for the replacement of the trucks, the digesters, the collectors, the photovoltaics, the storage units, the liquefaction units, the membranes, the heat exchangers, and all the auxiliary components. The correlations for the costs of all of the components can be found in previous works of the authors [33]. From the values calculated, is possible to calculate the main thermoeconomic indicators such as the Primary Energy Saving (PES), the Simple Payback (SPB), and the Net Present Value (NPV) [24]. Table 1 shows the main parameters used for the thermoeconomic analysis. More information about the costs of the components can be found in previous works of the authors [33].

Table 1. Parameters used in the thermoeconomic analysis.

Parameter	Description	Value	Unit
$c_{u,EE}$	Electricity purchasing cost	0.20	€/kWh
$p_{u,EE}$	Electricity energy exporting cost	0.05	€/kWh
c_{wc}	Woodchip purchasing cost	0.06	€/kg
$c_{u,Diesel}$	Diesel purchasing cost	0.805	€/L

https://doi.org/10.52202/069564-0157

LHV_{Diesel}	Diesel lower heating value	12.67	kWh/kg
LHV_{wc}	Biomass lower heating value	3.70	kWh/kg
LHV_{LNG}	LNG lower heating value	15.33	kWh/kg
LHV_{biogas}	Biogas lower heating value	5.86	kWh/Sm^3
J_{ETC}	Evacuated thermal collectors unit capital cost	300	€/m^2
J_{PV}	PV panels unit capital cost	1000	€/kW
J_{LIB}	Lithium-ion battery unit capital cost	200	€/kWh
$J_{CH\text{-}NH3}$	Ammonia chiller specific cost	2076	€/kW
J_{mem}	Membrane unit capital cost	50	€/m^2
J_{D2LNG}	Replacement unit cost from Diesel to LNG truck	84.72	k€/truck
M_{plant}	Plant yearly maintenance	1.5	%/year
K_{mr}	Membrane replacement price	25	€/m^2
v	Replacement rate	0.25	1/year
$\eta_{el,Grid}$	Electric efficiency of the public power grid	0.46	-
$\eta_{th,boiler}$	Thermal efficiency of the auxiliary heater	0.95	-
f_{EE}	Electric energy equivalent CO_2 emission factor	0.483	$kgCO_2$/kWhel
$f_{trucks,D}$	Diesel truck equivalent CO_2 emission factor	0.942	$kgCO_2$/km
CIC	Certificate of release for consumption	375	€/CIC

4. Case study

The techno-economic analysis of the proposed system is evaluated for a case study in the region of Campania, in the South of Italy. More specifically, the liquefied biomethane produced with the layout described is supposed to fully meet the fuel demand of a fleet of heavy-duty trucks. The trucks considered for the case study are the ones that everyday transport the containers (TEU) arriving as freight shipments in the port of Naples. The TEU are handled in the port and transported by means of heavy-duty trucks to the several distribution points where other TEU are withdrawn, in a continuous back-and-forth trading. According to the latest report of the Port System Authority [34], the total number of hinterland TEU daily handled in the port of Naples in 2022 was around 1440 TEU/day. The assumption of the model proposed is that half of these are incoming and half are outgoing, thus for each trade considered the trucks move one TEU from Naples to the distribution point and viceversa. On the base of this assumption, 720 heavy-duty trucks everyday take part to this trading system. The distribution points considered for the reference year are the cities of Caserta, Benevento, Isernia, Frosinone, Latina, and Salerno, see figure 4.

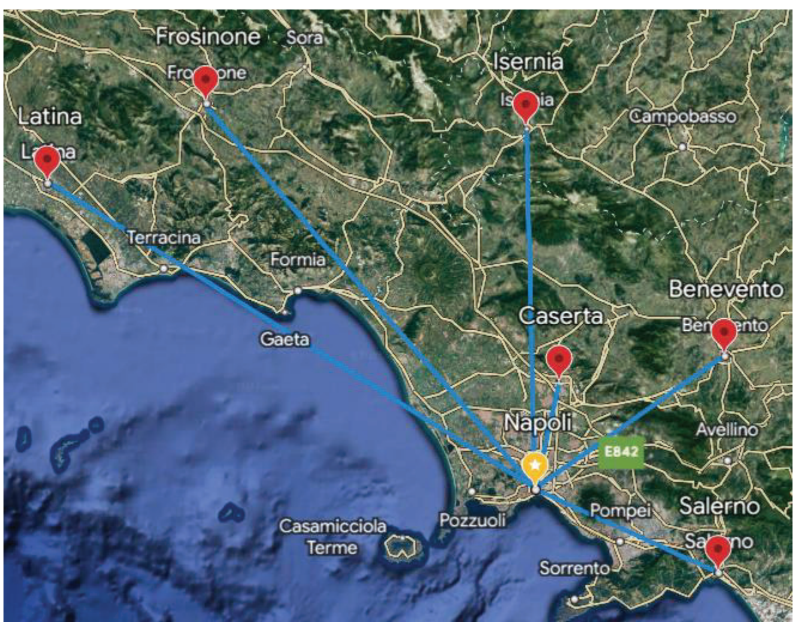

Figure. 4. Distribution map of the heavy-duty tracks transporting the containers.

Each truck runs for an average of 200 km every day mainly on highway roads, which means that the total distance daily covered by the fleet is 144´000 km/day. To cover this distance in the RS, 90´000 L/day of Diesel fuel are required, given a specific fuel consumption of 0.623 L/km [31]. According to data in table 1 and table

2, this fuel demand is equivalent to roughly $3.5x10^8$ kWh of primary energy, which is equivalent to roughly 23´000 tons/year of LNG. To meet this demand with the PS, the necessary amount of OFMSW needed is roughly 353´200 tons/year. According to data discussed in the "Report on Management of Municipal Waste in Campania" [35], around 625´000 tons/year of OFMSW are harvested, 65% of which come from the area of Naples, Caserta, and Salerno. Therefore, the biomass demand is fully met by the region and the collection points are possibly located very close to the TEU distribution points. In this case, 5 massive bio digestion plants are supposed to be dislocated in these areas, neglecting the energy costs for the fuel displacement due to the position with respect to the trucks displacements. Each plant is composed of 4 parallel PFRs of 2´580 m^3 operating with 2´016 kg/h of biomass and producing an average of 1´231 Sm3/h of biogas each. The biogas is then collected and sent to a membrane upgrading unit of roughly 2´850 m^2. Each plant is thus able to produce an average of roughly 530 kg/h which is sufficient to fully meet the LNG demand of the fleet. Detailed data regarding the case study are shown in table 2 and table 3.

Table 2. Main technical features of the case study proposed.

Parameter	Description	Value	Unit
δ_{trucks}	Distance covered by trucks	200	km/day
$Cs,_{Diesel}$	Diesel fuel truck specific consumption	0.623	L/km
ρ_{Diesel}	Density of the Diesel fuel	0.85	kg/L
M_{Diesel}	Mass of Diesel fuel required	27´922.5	tons/year
M_{LNG}	Mass of LNG required	23´077.5	tons/year
X	Rated quality of Linde Cycle	0.58	-
M_{bioCH4}	Rated flow rate of biomethane	6´272	kg/h
M_{OFMSW}	Organic municipal waste harvested in Campania	625´000	tons/year

Table 3. Technical data of the digesters.

Parameter	Description	Value	Unit
$\dot{m}_{OFMSW}$	Mass flow rate of OFMSW	2016	kg/h
ρ_{OFMSW}	Density of OFMSW	750	kg/m^3
$C_{p,\,OFMSW}$	Specific heat of OFMSW	2.72	kJ/(kg K)
$\dot{m}_{W,\,in}$	Mass flow rate of the inlet hot water range	1400÷9000	kg/h
T_{amb}	Ambient temperature range	-2 ÷ 35	°C
$T_{W,\,in}$	Inlet hot water temperature range	40 ÷ 60	°C
HRT	Hydraulic Retention Time	30	days
T_{dig}	Digester temperature	38	°C
H_{react}	Height of digester	10	m
n_{react}	Number of reactors operating in parallel	4	-
n_{plant}	Number of plants in operation	5	-

4. Results

The hourly, monthly, and yearly results of the simulation are presented and discussed in this section. Figure 5 shows the dynamic results for the electricity flow rates.

https://doi.org/10.52202/069564-0157

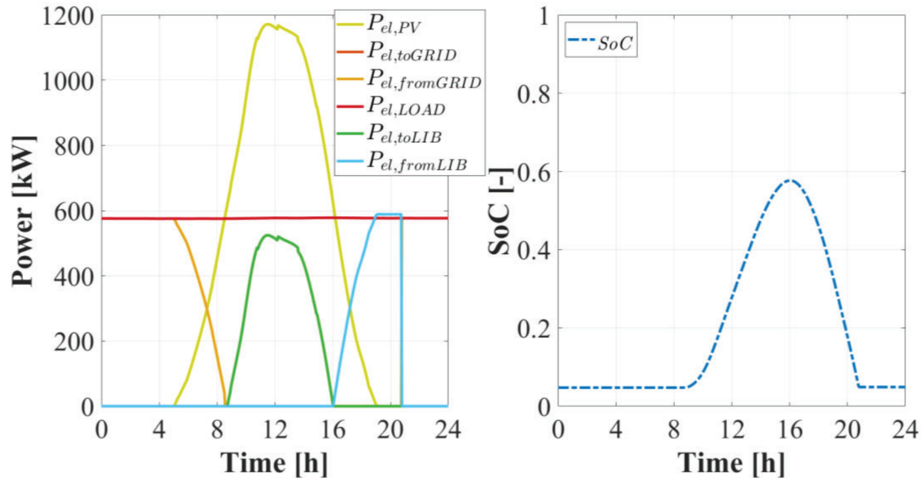

Figure. 5. Dynamic results for power flow rates.

The electricity flows shown here regard a single plant with 4 digesters operating with the biogas upgrading unit and the liquefaction cycle. The load of the plant is almost constant due to the possibility of operation in rated conditions, as it is common for optimal management of these technologies [29]. The day shown in figure 4 is a summer day so the electricity demand is met by the PV for large part of the day – 5 AM to 5 PM – with a remarkable fraction integrated with the battery in the other hours. In fact, the PV excess is relevant and the battery is filled up to roughly 60% allowing to extend the share of renewable power until 9 PM.

Figure 6 shows the monthly results of the simulation considering the total amount of energy for all the plants proposed.

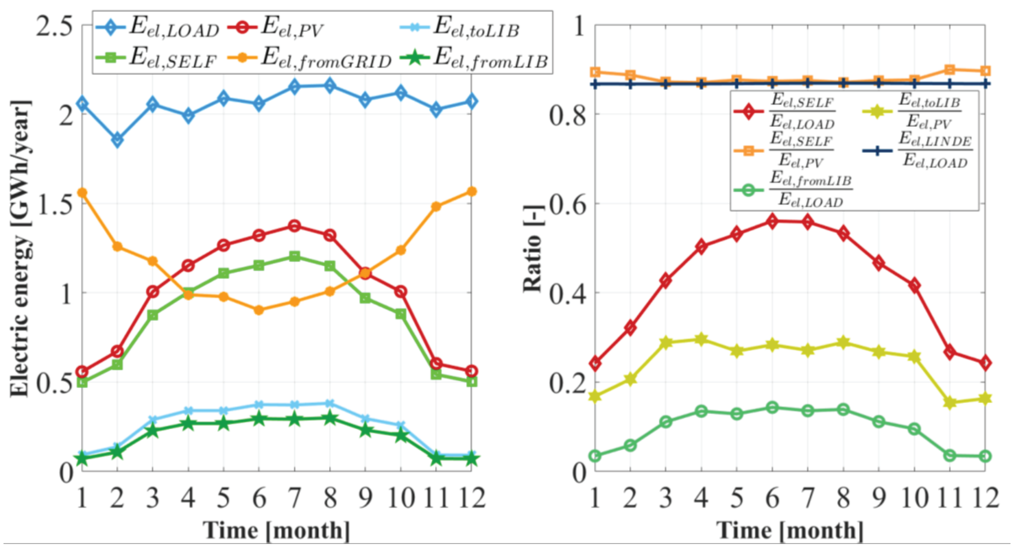

Figure. 6. Monthly results for the electric energies.

In the proposed system, the usage of the battery is pivotal to increase the share of renewables, since almost 30% of the PV energy is collected by the battery each month. The renewable fraction with respect to the PV energy, in fact, is constantly higher than 85%, see $E_{el,SELF}/E_{el,PV}$, and it reaches a peak of roughly 60% with respect to the total load in the summer period, see $E_{el,SELF}/E_{el,LOAD}$. The dynamic trend is thus confirmed and the battery is almost always fully exploited, with just a slight energy dispatching of few kWh in the summer period. However, the electricity sent to the grid is always negligible. This result is crucial since the production of bioLNG with this PS does not affect the electric grid and allows a great reduction of fossil fuel energy consumption. Furthermore, monthly trends also show that large fraction of the energy consumption is due to the liquefaction cycle, see $E_{el,LINDE}/E_{el,LOAD}$, as it was expected.

The trends discussed are confirmed by the results shown in Table 4. Furthermore, yearly results show a great economic feasibility of the solution presented.

Table 4. Results of the yearly analysis.

Parameter	Value	Unit
$E_{el,Upgrading}$	3.24	GWh
$E_{el,Linde}$	21.44	GWh
$E_{el,LOAD}$	24.71	GWh
$E_{el,fromGRID}$	14.22	GWh
$E_{el,toGRID}$	0.00	GWh
$E_{el,self}$	10.49	GWh
$E_{el,PV}$	11.95	GWh
$E_{el,toLIB}$	3.08	GWh
$E_{el,fromLIB}$	2.42	GWh
$E_{el,self}/E_{el,LOAD}$	0.424	-
$E_{el,fromLIB}/E_{el,LOAD}$	0.098	-
$E_{el,fromGRID}/E_{el,LOAD}$	0.575	-
$E_{el,toGRID}/E_{el,PV}$	0.000	-
$E_{el,self}/E_{el,PV}$	0.878	-
$E_{el,Upgrading}/E_{el,LOAD}$	0.131	-
$E_{el,Linde}/E_{el,LOAD}$	0.868	-
PE_{RS}	353.78	GWh
PE_{PS}	30.91	GWh
ΔPE	322.87	GWh
PES	0.91	-
$CO_{2,RS}$	49511.5	tons/year
$CO_{2,PS}$	6868.5	tons/year
ΔCO_2	0.86	-
$M_{biomethane}$	$5.5\ 10^7$	kg/year
M_{LNG}	$2.3\ 10^7$	kg/year
$M_{LNG}/M_{LNG,demand}$	1.00	-
C_{inv}	84.19	M€
C_{RS}	26.44	M€/year
C_{PS}	-20.33	M€/year
ΔC	46.77	M€/year
SPB	1.80	years
NPV	402.22	M€
PI	4.78	-

The primary energy consumption in the RS, when the Diesel fuel required is considered, is by far larger than the one of the PS. In fact, in this case only the amount of electricity withdrawn from the grid is responsible for fossil fuel consumption since the bioLNG produced meets all the fuel demand of the fleet of trucks, and the PES is equal to 91%. At the same time, the CO_2 emissions are reduced by 86%, also due to the fact that the thermal energy demand of the digesters is fully met by renewables, ETC and auxiliary biomass-fed boilers.

The economic feasibility is due to strong incentives both for the usage of bio-fuelled trucks and the production of biomethane from organic municipal wastes. In fact, Italian Government provides double fundings both for the purchase of bioLNG trucks and the dismissal of old Diesel fuelled trucks, and for the production and selling of “advanced” biomethane produced from organic wastes. In this case, the relevant capital costs of such a proposed solution, higher than 84 M€, are widely justified by the great reduction of the operative costs which lead to a yearly money saving of 46.77 M€/year. The fundings due to the CIC for biomethane vastly overcome the extra costs necessary for the maintaining of the plants and the withdrawal of electricity form the grid. The outstanding result in terms of profitability of the solution is highlighted by the NPV which is equal to 402 M€, almost five times the initial investment.

Figure 7 shows a parametric analysis considering different prices for the purchasing of urban waste for the disposal. In fact, Government may pay the ones who assume the responsibility of the urban wastes disposal.

https://doi.org/10.52202/069564-0157

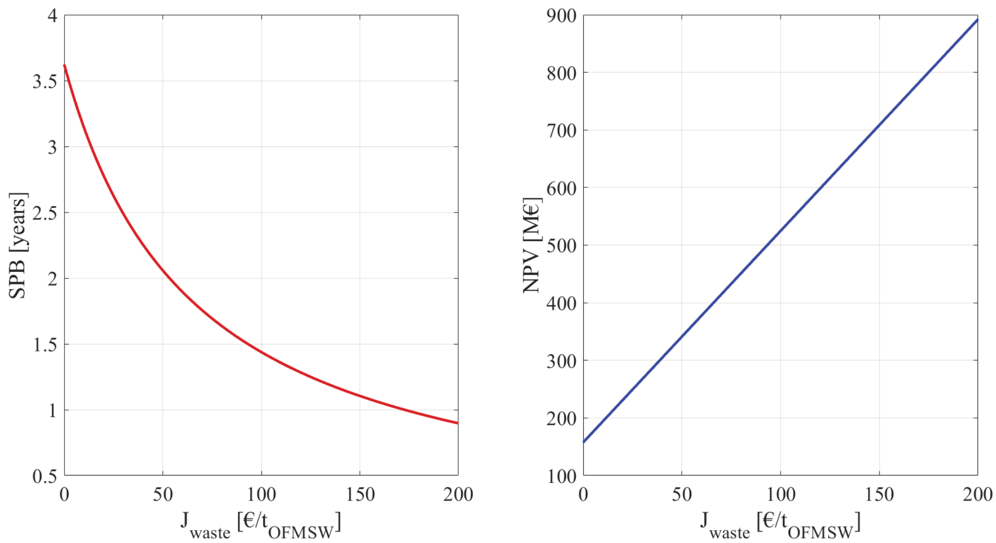

Figure. 7. Dynamic results for power flow rates.

The purchasing price for the disposal (J_{waste}) ranges from 0 to 200 €/ton of waste, treated to be used as biomass for the anaerobic digestion plants. In this case the CIC were not considered in the calculation of the economic indexes since with CIC the biomethane produced is already paid twice because of the treatment of the organic fraction of municipal solid wastes. In this case the SPB of the system could be even more profitable when the value of J_{waste} is greater than 70 €/ton. The same occurs for the NPV, with a constantly linear increase. It is worth noting that further increasing of J_{waste} over 250 €/ton would not come with relevant beneficial effect on the SPB of the system.

5. Conclusion

This work proposed a thermoeconomic analysis of a liquefied biomethane production plant proposed for several cities in the region of Campania, in the South of Italy. The proposal of these plants was to meet the fuel demand of a fleet of Diesel fuelled heavy-duty trucks which transport containers back and forth from the port of Naples. The main results obtained from the dynamic simulation and thermoeconomic analysis of the model proposed are the following:

- Five plants each one including four plug flow reactors operating 2016 kg/h of organic fraction of municipal solid wastes are able to fully meet the fuel demand of the fleet, equal to roughly 23000 tons/year of liquefied biomethane.
- The system proposed has large share of renewables since the thermal demand of the digesters is met by evacuated tube collectors and biomass fed boilers. In fact the Primary Energy Saving is remarkable and equal to 91%. At the same time the CO2 equivalent emissions avoided are equal to 86%.
- In addition, the system shows also great economic feasibility due to the grants provided by the Italian Government for the production of biomethane. Furthermore, relevant discounts are offered for the purchasing of green trucks, resulting in a Simple Payback of 1.8 years. The profitability is also shown by the Net Present Value equal to roughly 422 M€.
- Considering a premium tariff for the purchase of the urban wastes would increase the profitability of the system even more than the incentives for the selling of biomethane. In this case the Simple Payback and the Net Present Value would be even higher with a value of this tariff greater than 70 €/ton of waste.

Acknowledgments

Italian national research project:

PRIN 2020: OPTIMISM – Optimal refurbishment design and management of small energy micro-grids, funded by the Italian Ministry of University and Research (MUR).

Nomenclature

c specific cost [euro/kWh]

C operating cost [euro/y]
E energy [kWh/y]
h specific enthalpy [kJ/kg]
J capital cost [euro]
LHV lower heating value [kWh/kg]
M maintenance [euro/year]
m mass flow rate [kg/s]
M mass flow rate [kg/y]
OFMSW organic fraction of municipal solid wastes
PE primary energy [kWh/y]
T temperature [°C]
x quality [-]

Subscript

c compressor
dig digester
el electric
f emission factor [$kgCO_2$/kWh or $kgCO_2$/kg]
HE heat exchanger
iso isentropic
LNG liquified natural gas
D diesel
p pressure
PS proposed system
RS reference system
TK tank

Greek symbol

β compression ratio [-]
ε heat exchanger effectiveness [-]
ω heat capacity ratio [-]
η efficiency [-]

References

1. Parliament, E., *Resolution of the European Green Deal. p. RSP.* 2019.
2. Köhl, M., et al., *The EU climate package "Fit for 55" - a double-edged sword for Europeans and their forests and timber industry.* Forest Policy and Economics, 2021. **132**: p. 102596.
3. EEA. *Share of transport GHG emissions*. 2020; Available from: <https://www.eea.europa.eu/data-and-maps/daviz/sds/share-of-transport-ghg-emissions-4/@@view>.
4. Chiaramonti, D., et al., *The challenge of forecasting the role of biofuel in EU transport decarbonisation at 2050: A meta-analysis review of published scenarios.* Renewable and Sustainable Energy Reviews, 2021. **139**: p. 110715.
5. Mandley, S.J., et al., *EU bioenergy development to 2050.* Renewable and Sustainable Energy Reviews, 2020. **127**: p. 109858.
6. Goetz, A.R., *Intermodality*, in *International Encyclopedia of Human Geography*, R. Kitchin and N. Thrift, Editors. 2009, Elsevier: Oxford. p. 529-535.
7. Giuliano, G., et al., *Heavy-duty trucks: The challenge of getting to zero.* Transportation Research Part D: Transport and Environment, 2021. **93**: p. 102742.
8. Council, E. *Fit for 55: towards more sustainable transport*. 2022; Available from: https://www.consilium.europa.eu/en/infographics/fit-for-55-afir-alternative-fuels-infrastructure-regulation/.

https://doi.org/10.52202/069564-0157

9. Feng, Y. and Z. Dong, *Comparative lifecycle costs and emissions of electrified powertrains for light-duty logistics trucks.* Transportation Research Part D: Transport and Environment, 2023. **117**: p. 103672.
10. Küffner, C., *Multi-level perspective for the development and diffusion of fuel cell heavy-duty trucks.* Transportation Research Part D: Transport and Environment, 2022. **111**: p. 103460.
11. Scopus. *Article search*. 2023; Available from: https://www.scopus.com/term/analyzer.uri?sort=plf-f&src=s&sid=4fd4e27465bd22d7fe2a51c2d07679ab&sot=a&sdt=a&sl=27&s=TITLE-ABS-KEY%28green+trucks%29&origin=resultslist&count=10&analyzeResults=Analyze+results.
12. Lajevardi, S.M., J. Axsen, and C. Crawford, *Examining the role of natural gas and advanced vehicle technologies in mitigating CO2 emissions of heavy-duty trucks: Modeling prototypical British Columbia routes with road grades.* Transportation Research Part D: Transport and Environment, 2018. **62**: p. 186-211.
13. Quiros, D.C., et al., *Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport.* Atmospheric Environment, 2017. **168**: p. 36-45.
14. Kiehbadroudinezhad, M., et al., *The role of biofuels for sustainable MicrogridsF: A path towards carbon neutrality and the green economy.* Heliyon, 2023. **9**(2): p. e13407.
15. Wang, L., et al., *Power-to-fuels via solid-oxide electrolyzer: Operating window and techno-economics.* Renewable and Sustainable Energy Reviews, 2019. **110**: p. 174-187.
16. Barros, R.S., et al., *Evaluation of the methanogenic potential of anaerobic digestion of agro-industrial wastes.* Heliyon, 2023: p. e14317.
17. Hosseini, S.S., et al., *Progress in high performance membrane materials and processes for biogas production, upgrading and conversion.* Separation and Purification Technology, 2023. **310**: p. 123139.
18. Gkotsis, P., et al., *Biogas upgrading technologies – Recent advances in membrane-based processes.* International Journal of Hydrogen Energy, 2023. **48**(10): p. 3965-3993.
19. Naquash, A., et al., *State-of-the-art assessment of cryogenic technologies for biogas upgrading: Energy, economic, and environmental perspectives.* Renewable and Sustainable Energy Reviews, 2022. **154**: p. 111826.
20. Baccioli, A., et al., *Small scale bio-LNG plant: Comparison of different biogas upgrading techniques.* Applied Energy, 2018. **217**: p. 328-335.
21. Naquash, A., et al., *Renewable LNG production: Biogas upgrading through CO2 solidification integrated with single-loop mixed refrigerant biomethane liquefaction process.* Energy Conversion and Management, 2021. **243**: p. 114363.
22. Hashemi, S.E., et al., *Cryogenic vs. absorption biogas upgrading in liquefied biomethane production – An energy efficiency analysis.* Fuel, 2019. **245**: p. 294-304.
23. Gustafsson, M., et al., *Scenarios for upgrading and distribution of compressed and liquefied biogas — Energy, environmental, and economic analysis.* Journal of Cleaner Production, 2020. **256**: p. 120473.
24. Calise, F., et al., *Concentrating photovoltaic/thermal collectors coupled with an anaerobic digestion process: Dynamic simulation and energy and economic analysis.* Journal of Cleaner Production, 2021. **311**: p. 127363.
25. Ghorbani, B., et al., *Energy, exergy and pinch analyses of a novel energy storage structure using post-combustion CO2 separation unit, dual pressure Linde-Hampson liquefaction system, two-stage organic Rankine cycle and geothermal energy.* Energy, 2021. **233**: p. 121051.
26. Calise, F., et al. *Modeling of the Anaerobic Digestion of Organic Wastes: Integration of Heat Transfer and Biochemical Aspects*. Energies, 2020. **13**, DOI: 10.3390/en13112702.
27. Calise, F., et al., *Dynamic analysis and investigation of the thermal transient effects in a CSTR reactor producing biogas.* Energy, 2023. **263**: p. 126010.
28. Al-Obaidi, M.A., C. Kara-Zaïtri, and I.M. Mujtaba, *Performance evaluation of multi-stage reverse osmosis process with permeate and retentate recycling strategy for the removal of chlorophenol from wastewater.* Computers & Chemical Engineering, 2019. **121**: p. 12-26.
29. Cappiello, F.L., et al. *Thermoeconomic Analysis of Biomethane Production Plants: A Dynamic Approach*. Sustainability, 2022. **14**, DOI: 10.3390/su14105744.
30. Calise, F., et al., *A novel tool for thermoeconomic analysis and optimization of trigeneration systems: A case study for a hospital building in Italy.* Energy, 2017. **126**: p. 64-87.
31. Tratzi, P., et al., *Liquefied biomethane for heavy-duty transport in Italy: A well-to-wheels approach.* Transportation Research Part D: Transport and Environment, 2022. **107**: p. 103288.
32. Hartmann, P., A. Marcos, and J.M. Barrutia, *Carbon tax salience counteracts price effects through moral licensing.* Global Environmental Change, 2023. **78**: p. 102635.
33. Calise, F., et al., *Dynamic simulation modelling of reversible solid oxide fuel cells for energy storage purpose.* Energy, 2022. **260**: p. 124893.
34. Authority, P.S., *Port of Naples displacements - updated to 22-12-22*. 2022.
35. region, C., *Report on Management of Municipal Waste in Campania*. 2020.