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BIOMETHANE, A NEW DIRECTION FOR BIOGAS UTILIZATION

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Abstract: After decades of delay, Hungary has announced a subsidy scheme aimed at utilizing the available biomass potential for advanced biomethane production. Due to environmental sustainability guidelines such as carbon neutrality, transport, like many other industries, faces serious challenges, some of which are energy-related. Biogas plants and the emitters that supply them with raw materials, such as agricultural and food industry by-products and municipal waste, can make a significant contribution to the transition to carbon-free transport. In this article, we aim to highlight that instead of traditional energy solutions, the use of biomass for transportation purposes is not only a viable option, but may even be the most profitable technology for investors.

Keywords: carbon-neutral technologies, biomethane-based gas plant, alternative bio LNG+CCS liquefaction, Island-operated renewable energy system

1. Introduction

The aim of the subsidy call is to promote the green transition in the field of molecules. The primary goal is to increase the production of biogas and biomethane, thereby replacing natural gas, and to increase the use of electricity, heat energy, and fuel (bioLNG, bioCNG) produced from it. An important consideration in the implementation of these developments is compliance with the principle of environmental sustainability, with particular regard to the biological raw materials used. In the spirit of circular economy, the aim is to use the biological end product, biogas manure, as a soil replenishment material in agriculture [1], [2].

If the subsidy achieves its goal, investments in biomethane plants may also boom in Hungary, following European trends. According to the European Biogas Association (EBA) estimates that the number of European biomethane plants will rise to 1,678 by the first quarter of 2025, which represents an average annual increase of 182.8 plants over the five-year period from 2020 to 2024 (Figure 1). Hungary has 3 biomethane plants. which is less than 2 per thousand [3].

The importance of the sector should be emphasized; the European sector and the political target expect annual biomethane production in Europe to reach 35 billion cubic meters by 2030. This figure is close to 10% of total primary gas consumption. Fact: By 2023, 4.9 billion cubic meters of biogas out of 22 billion cubic meters will be used in the form of biomethane. As Dekker (2025) highlighted the European Biogas Association (EBA) plays a crucial role in facilitating the achievement of the biomethane target and the further ramp up towards 2050, through several activities:

- Advocacy and Policy Work: EBA actively engages with EU policymakers to promote supportive legislation and frameworks that encourage biomethane production and use. The Biomethane Industrial Partnership plays an important role in this work.

- Knowledge Sharing and Best Practices: The association provides a platform for members to share experiences, technologies, and best practices, helping to improve efficiency and effectiveness in the sector.
- Capacity Building: EBA offers training and resources to stakeholders to enhance skills and knowledge related to biogas and biomethane production.
- Market Development: By promoting the benefits of biomethane, EBA helps to create demand and stimulate investment in the biogas sector across Europe [4], [5].

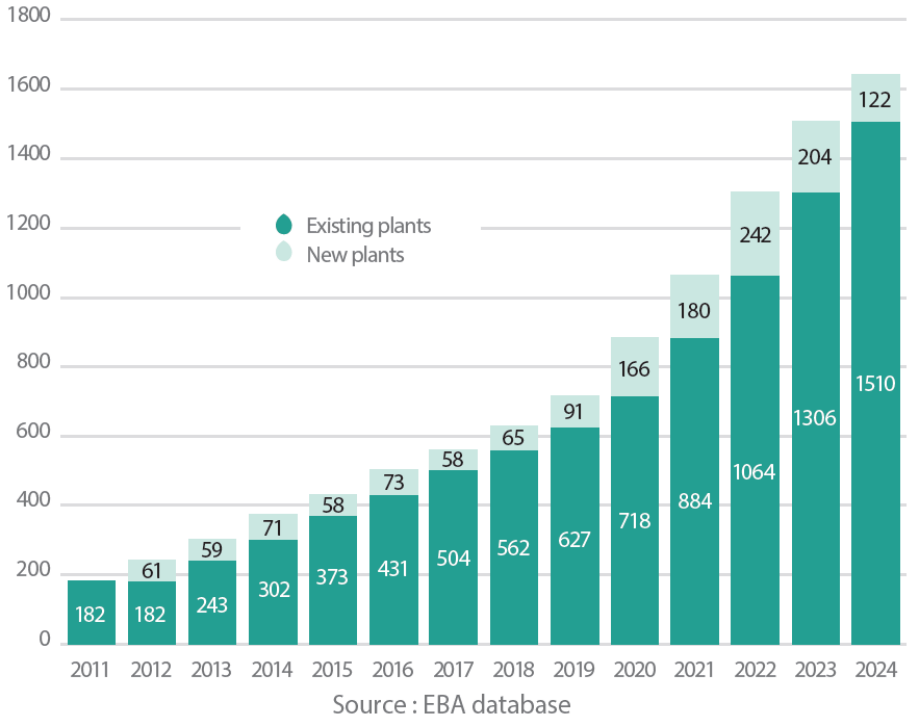

Figure 1. Growth in the number of biomethane plants in Europe between 2011 and 2024 [3]

Szunyog (2009) focused on the EBA records: 86% of European biomethane plants are connected to the European natural gas pipeline network, meaning that pipelines are used to distribute the majority of methane produced from biogas [6].

According to Kroon (2014) in addition to pipeline transport, there are a small number of local compression (CNG) or liquefaction (LNG) plants, which use transport technologies other than pipelines [7].

2. Overview of the biomethane production technologies

It is widely known among professionals that in recent years, or rather decades, biogas plants have not been among the most popular investment targets in Hungary. Reason for this are the high investment costs, environmental impacts (e.g., odor), and operational problems arising from the interaction of biological and technical systems and the complexity of the technology Tóth at al. (2014) revaled the most important determining factors of the technological issues deriving from the input materials and the process elements. [8]. in their research. Bártfai at al. (2015) conducted operational experiments to investigate the causes of foaming in the fermenter. According to the research results, the preparation of input materials (e.g., the quality of fiber raw material shredding), the feeding ratio of material types, and the mixing characteristics of the material in the fermenter have a significant impact on the technological process [9]. Based on real operational tests Tóth et al (2015) concluded foaming is particularly disadvantageous in terms of gas formation [10].

Another reason why the biogas plants are not viewed favorably is the produced biogas was converted into electricity by generators, which – especially in the case of continuous power generation – provided only a small income [11], [12].

As Steppat (2025) stated, a recently emerging form of biomethane utilization is peak-time electricity generation instead of continuous electricity generation, which could ensure a significantly higher purchase price per unit of energy carrier. However, storing the biogas produced in an environment close to atmospheric pressure results in low, mostly insufficient capacity. An even more cumbersome and, in terms of overall efficiency, unfavorable technical solution is the storage of the generated electricity in batteries prior to feeding it into the grid [13].

Compared to traditional (widespread) biogas technology, a step forward is to ensure the storability of the energy carrier with relatively high capacity by liquefying the separated methane molecules from the produced gas. As a result of liquefaction, methane gas in its cryogenic state requires approximately 600 times less volume than in its normal state, making it practical to store and transport. In this case, only adequate thermal insulation needs to be provided, which can usually be achieved safely in double-walled vacuum-insulated containers.

Liquefied methane offers a wide range of uses: the generator plant can only produce electricity during the hours when the grid feed-in price is at its highest, and not only locally at the biogas plant where the generator park was built, but also in isolated operation at any location.

The transformation of global energy supply systems is increasingly moving towards sustainability, decarbonization, and energy independence. Balogh et al. (2025) draws attention to the particular interest in renewable energy sources based on solar and wind energy, which can be used flexibly (scalable), even mobile, and installed anywhere (e.g., in container designs), known as stand-alone energy production and supply systems. One of the main reasons for this is that, compared to grid-based energy supply systems, they are autonomous, to a certain extent independent, and capable of local energy supply. In the case of mobile installation, they can provide electricity supply within a short period of time, e.g., to a facility located in an area without infrastructure or to a disaster- or war-stricken area. In order to make the energy supply more stable, these kinds of renewable power plants can be can be supplemented with additional energy sources, such as biomethane. Figure 2. shows a concept of this system.

However, it should be noted that the operation of such systems poses new technological and system integration challenges, particularly in the areas of stable biogas plant operation and energy storage [14].

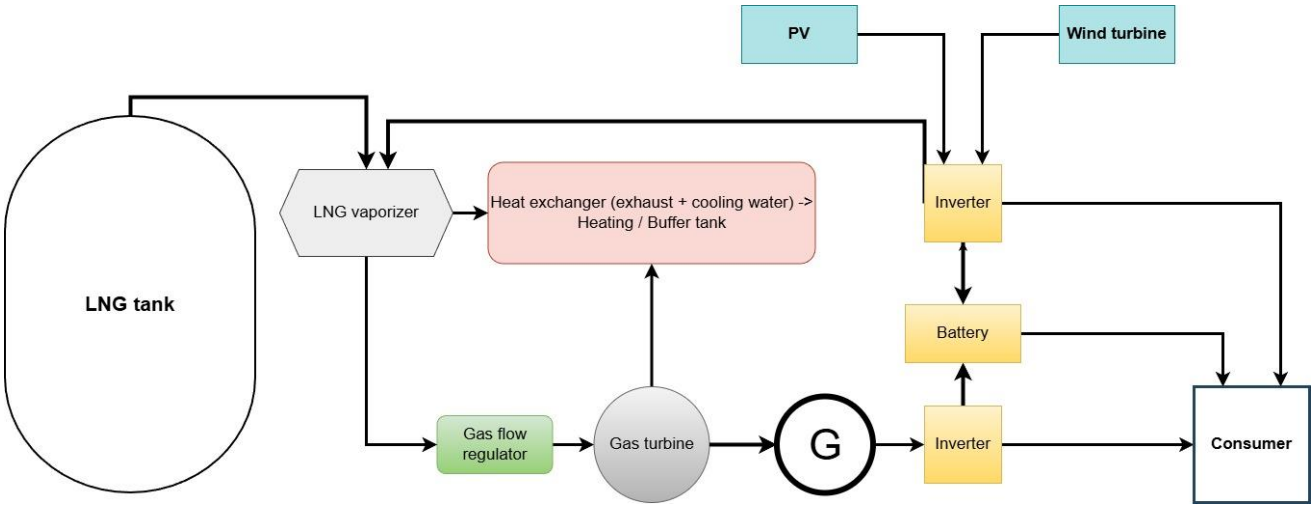

Figure 2. Concept of an island energy system based on renewable energy sources [11]

Gaster (2024) confirms that this application is appropriate, increasingly important and can provide a good solution for balanced, evenly loaded network operation, as the capacity of gas generators can flexibly balance the deficit in electricity generated by solar cells, or even wind generators can be flexibly balanced by the capacity of gas generators [15].

Munnings (2023) in his report deals with the today's energy problems and solutions. Efficient, flexible, and environmentally friendly energy storage solutions are essential for balancing weather-dependent production

The increasing capacity of solar and wind renewables requires the establishment of parallel generator capacity (this means technology that ensures flexibility, which is increasingly necessary for the stability of grid frequency), in which case the use of methane from biogas is an obvious element of decarbonization processes [16].

Figure 3. shows a realized island-operated liquefied methane regasification station.

Figure 3. Island-operated liquefied methane regasification station with a 1 MW Capstone turbine system for generator drive and other auxiliary consumers [17]

3. Transportation purpose

In addition to the use of methane molecules for thermal energy and power generation, the importance of its use in transportation is often overlooked. Transport accounted for around a quarter of the biomethane produced in Europe, which means powering LNG and CNG vehicles. Transport is the most difficult and costly sector to decarbonize. Regardless of political will, electrification alone does not mean carbon-free transport, as this would require electricity generation to be completely free of fossil fuels, which will not be possible for decades, and not all sectors can switch to electric operation. In particular, it is more practical to use the significantly more cost-effective, tried and tested alternative of gas propulsion for heavy-duty vehicles, ships, railways, and even agricultural machinery such as tractors. A practical study performed by Bäckström and Jivén (2022), comparing the operation of BioLNG-powered vehicles and their diesel counterparts showed a significant improvement in "climate efficiency" with the same energy consumption, resulting in an advantage of up to -330% for biomethane-powered vehicles [18].

To illustrate that the transition to gas propulsion is progressing at an accelerated pace in many markets, here are some statistics from two markets:

- The amount of LNG used at LNG filling stations in Italy in 2024 will be 220,000 tons, and in Germany 240,000 tons. In both countries, significant CNG consumption (especially in Italy) is above this level.
- In Finland, the market share of newly registered gas-powered heavy-duty vehicles will be 48% in 2024, with the entire LNG fleet running on BioLNG. In Norway, this share is 15%.
- In China, which is also mentioned as a leader in electrification, 30% of the new heavy-duty vehicle market was LNG-powered in 2024, and this figure rose to over 50% in the second quarter of 2025. The amount of LNG served at roadside LNG filling stations reached 30 million tons annually.

According to the relevant surveys (Lam 2021, IMO 2021) the transition of road transport, and heavy-duty vehicles in particular, to gas propulsion creates a significant demand for LNG. The rise in this volume will certainly be visible in the coming years. In the field of maritime shipping, no other alternative seems to be emerging, as LNG propulsion appears to be the only economical alternative that can offer shipping companies lower operating costs and a faster return on investment compared to petroleum-based propulsion [19], [20].

In the transition to carbon-free transport – which should rightly be referred to as fossil-free – gas-powered vehicles, and within that, biomethane, for which the most appropriate term is carbon neutrality, should play a prominent role. The transport sector's increased capacity for renewable methane is clearly evident from the

statistics. By 2023, transport already accounted for 23% of European biomethane consumption, followed by heating in buildings (17%), electricity generation (15%), and industrial use (13%)

The options for delivering biomethane to vehicle filling stations are not very diverse. In the case of LNG vehicles, the gas must be delivered to the site in liquefied form, therefore

- either the biomethane is liquefied at the biomethane plant and distributed to filling stations, or
- in the absence of this, the gas must be transported from the LNG import terminal to the filling points and the renewable molecules injected into the pipeline network are sold to the filling stations as Guarantees of Origin for Renewable Gases (known in technical jargon as Certificates). The legal framework for the growing Certificate trade in Europe has already been established in Hungary.

Thanks to the Certificate trade, vehicle operators refuel with biomethane at the vast majority of CNG filling stations in Europe, thus achieving carbon-neutral transport. It should never be overlooked that the ideological-based categorical ban on internal combustion engines can be described, at the very least, as a serious mistake.

In the case of CNG, certificate trading is obvious, since compressed natural gas, unlike LNG, is typically produced by compressors connected to the pipeline network, meaning that molecules taken from the gas pipeline are filled into vehicles.

In the case of LNG, shipments can be equipped with renewable certificates through import terminals. Given that import terminals regasify LNG transferred from tankers and transport it to consumers via pipelines, most of them also have smaller liquefaction capacities for handling boil-off gas (i.e., gas that evaporates in the tank). If the re-liquefied molecules are supplemented with certification, it becomes possible to sell the desired amount of renewable LNG.

This is, of course, an effective solution if the distance over which the LNG is transported does not make the energy carrier disproportionately expensive. In the middle of the continent, however, the transport distance can exceed 1,500 kilometers, which significantly affects the cost of the fuel that can be sold and worsens its market position. It is precisely this transport cost that gives biomethane liquefaction plants a competitive advantage, as liquefaction plants located in the interior of the continent are exempt from significant transport distances.

3.1. Establishment of a biomethane plant and transportation of the molecule via pipeline

According to the stated support objectives, the biomethanation technology of biogas plants with a yield of over 500 m^3/h can be developed. Referring back to publication on biogas liquefaction (Bártfai et al. 2019), the main element in separating the various molecules present in biogas is the highly efficient separation of carbon dioxide and methane [21].

The industry has developed different processes for this purpose. Bártfai et al. (2020) summarized the well spread technologies (Figure 4.). The costs of each technology and the level of methane purity achievable also vary.

The phase following the production of biomethane involves the transportation of the gas, its injection into natural gas pipelines, or its transportation in CNG or LNG form by other means.

In order to develop a biogas and biomethane strategy, the preparatory material compiled by FGSZ described the technological requirements and cost spectrum for connecting to different categories of natural gas pipelines as follows [22].

Biomethane producers can connect:

- only to the distribution network (DSO, ~6 bar),
  - -possibly with reverse flow implementation, or
- to the natural gas transmission network (TSO, 40-63 bar),
  - -independently with a transmission system connection, or
  - -with a "hybrid" (distribution and transmission system) connection
  - -or with a hybrid connection in the case of multiple plant pooling.

The following requirements must be met on the biomethane plant side:

- monitoring of biomethane quality and, if necessary, installation of an automatic flaring system,
- installation of odorization in accordance with regulations,
- installation of pressure boosting technology.

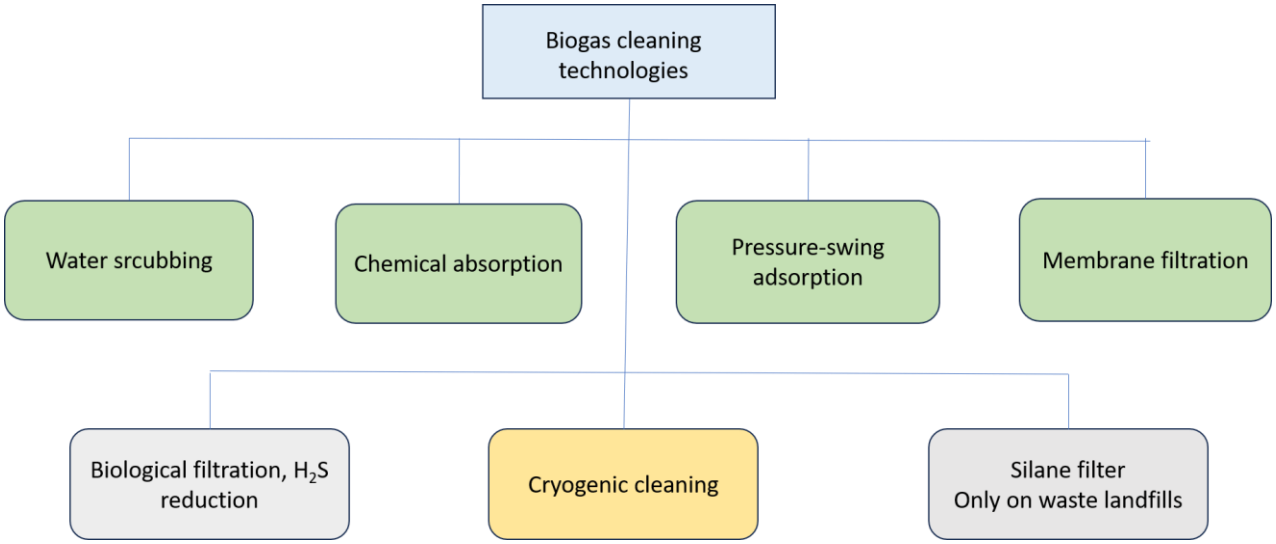

Figure 4. Summary of the range of biogas cleaning technology solution [23]

In the case of energy-related investments, another important decision-making factor is the assessment of operating costs after construction and the direct and indirect economic effects related to production. In addition to the above, the plant must also bear the costs of constructing the connecting pipeline and operating all of the above [24, 25].

In order to ensure natural gas quality, in addition to separation technology, the biomethane plant can expect to incur investment costs of approximately HUF 200-300 million at current values. An additional HUF 80-150 million must be added for the pressure increase, while the cost of the connecting pipeline is around HUF 50 million per kilometer in the case of the DSO system, but between HUF 80 and 150 million in the case of the TSO, according to FGSZ data.

Connection to the medium-pressure natural gas system is only possible if the biomethane flow is lower than the current natural gas flow in the distribution pipeline, in which case the technical implementation costs on the FGSZ side can reach up to HUF 130 million.

If reverse flow from the medium-pressure system (DSO) to the transmission system (TSO) is required because the amount of biomethane produced may exceed the consumption of the given medium-pressure system, the gas pressure must be increased to 40-63 bar in the transmission pipeline. The cost of this development on the part of FGSZ is HUF 1-1.2 billion.

If the biomethane plant connects to the natural gas transmission system independently, the cost of the necessary development is HUF 540-700 million, depending on whether an existing or new FGSZ gas transfer station is to be built. In addition, the cost of building the necessary compressor has been estimated at between HUF 800 million and HUF 2.6 billion, which will be borne either by FGSZ or the biomethane plant.

Hybrid connection means connection to the DSO and TSO pipelines. On the biomethane plant side, the lower pipeline construction costs and lower compressor costs (to the DSO) while on the FGSZ side, the costs of connecting to the preferred existing gas transfer station were estimated at HUF 712 million, to which the cost of compressor construction was added, scaled to the connection of an independent natural gas transmission system.

In the case of joint network connection (pooling) of biomethane plants, the costs of the hybrid connection are shared to some extent among the biomethane plants connected. The cost of compressor installation is shared among the participants in the pooling.

The determination of multiple cost items significantly delays the preparation of an investment in a biomethane separation plant and represents a relative uncertainty in terms of costs. Furthermore, it can significantly delay the implementation of the project, even by years, which also poses a risk from a financing perspective.

It can be stated that for a 500-1000 m^3/h biogas plant, whose gas separation technology starts at a cost of between HUF 1 and 1.5 billion, the costs associated with connecting to a DSO network 10 km away are estimated at HUF 1.2 billion in the most favourable case. For larger plants, the latter connection can reach HUF 5 billion. Annual maintenance and operating costs can start at HUF 200 million.

3.2. Establishment of a biomethane plant and transport of the molecule on an axis

Methane separated from other components of biogas can be transported economically by road as a result of liquefaction, over a wider distribution area, up to a radius of 4-500 km. This is a striking difference compared to compression technology (CNG) at 200 or even 250 bar, where economic considerations do not allow for transport distances greater than 30-40 km. The reason for this is that a vehicle combination with a total weight of 40 tons can transport 18-20 tons of LNG, while in the case of CNG, this is no more than 4-4.5 tons. In the case of LNG, the efficiency of transport is demonstrated by the fact that a single vehicle can transport 40-50 tons of gas per day in a production and distribution area the size of Hungary, which means that it is capable of transporting the output of several biogas plants – with a total hourly yield of up to 5,000 cubic meters – to consumption points. This can result in up to 750 MWh of energy per vehicle per day.

Figure 5. shows a special vehicle suitable for the road transport of gas produced using cryogenic technology (converted to a liquid state at extremely low temperatures).

Figure 5. Cryogenic gas transport vehicle for LNG transport [26]

The requirements for biogas separation prior to liquefaction are similar to those for feeding into the natural gas system, with the difference that in biomethane, water vapor and hydrogen sulfide may only remain at a level of a few tens of ppm, and the CO_2 content may not exceed 200 ppm. However, achieving higher purity gas does not result in significantly higher costs, although in the case of CO_2 it reduces the range of possible technologies. Depending on the complexity of the raw material, a biogas treatment plant in the 500-1000 m3/h production category requires an investment of HUF 300-500 million for preparation, plus an additional HUF 700 million to HUF 1.5 billion for CO_2 separation.

It should be noted that the CNG route has significantly lower requirements in terms of carbon dioxide separation, and can therefore be implemented at a lower investment cost.

The technologies available for the liquefaction of separated biomethane become significantly more expensive for smaller gas yields. The products available on the market range from €4 to €15 million, with daily production values of 2-15 tons, and at least another €1 million must be added for installation. For conversion, approximately 10 tons of LNG can be produced from a 1000 m3/h biogas plant.

Summing up the figures, it can be concluded that the establishment of the plant – again, without the biogas plant – can be planned with an investment cost of HUF 3.5-5.5 billion, within the previously calculated biogas yield range.

4. Alternative BioLNG+CCS liquefaction technology

The latest technological proposals from Cryonex Industries ZRt offer investors in biogas plants carbon dioxide separation integrated into the cooling process. This provides three significant advantages:

- The investment cost of carbon dioxide separation is reduced by 10-30 percent
- The cost of liquefaction technology also becomes more favorable in relative terms
- Carbon dioxide in its liquefied state appears as a marketable product, Bio-CO_2, with a food-grade purity of >99.95%, contributing significantly to the operating result.

In other words, Carbon Capture & Storage (CCS) is also achieved, which cannot be provided by any of the processes considered so far or any other use of biogas. This is a significant added value, the impact of which should be given special attention when preparing the CO2 balance and should be positively distinguished.

The essence of the liquefaction technology offered lies in the closed cooling unit (cold box). Inside the cooling unit, a multi-stage heat exchanger system operates with a circulating gas mixture cooling medium. The circulating return gas mixture is compressed and then passed through a Joule-Thomson valve, where it reaches a temperature of ~-156 °C, which gradually reduces the temperature of the treated gas through the Cold-box heat exchangers. During the process, more than 99.95% of the CO_2 molecules freeze out of the biogas stream, while the remaining CH_4, O_2, and N_2 molecules pass through. During the process, more than 99.95% of the CO_2 molecules freeze out of the biogas stream, while the remaining CH_4, O_2, and N_2 molecules are cooled to -156 °C. In a condenser vessel, the methane separates from the remaining gas stream and becomes liquid. The non-liquefied O_2- and N_2-rich residual gas, with a CH_4 content of approximately 20%, is also utilized and provides about a quarter of the fuel for the 400 kW generator that supplies the plant's power needs. The plant provides the additional fuel required from the boil-off gas of the LNG tank.

In the cold box, the CO_2 snow crystals melt and are transported in liquid form to the cryogenic LCO_2 tank by the pump. The LNG and LCO_2 cryogenic tanks are connected to a cryogenic tank vehicle service terminal. The plant selected as an example produces one full shipment of carbon dioxide per day and one shipment of biomethane every two days.

For the sake of comparability with the figures presented in the previous chapters, here are some selected data from the technical proposals prepared by Cryonex Industries ZRt. for the technological development of a low-pollution biogas yield plant:

- The planned yield of the biogas plant is 900 m^3/h, which means a gas flow of approximately 1100 kg/h.
- The investment cost of the BioLNG & CCS plant is in the range of HUF 2.5-3 billion, which includes the generator that supplies the plant's electricity consumption, which also ensures the destruction of the liquefaction residue gas, as well as the costs of storing the products and loading them into tanker vehicles
- Based on 8,400 operating hours per year, the products supplied amount to 2,560 tons of LNG and 5,590 tons of LCO2 (liquefied carbon dioxide), which is supplemented by a 39.5 GWh certificate (the guarantee letter is issued for this amount of energy).
- Following operating expenses in the range of HUF 200-250 million (not including the raw material and operating costs of the biogas plant), the annual net revenue available at current prices is approximately HUF 1.4 billion from the sale of BioCO2 and the sale of Certificates, BioCO_2 sales, and certificate sales.

5. Advantages of establishing a biomethane liquefaction plant

In the case of a biomethane plant, the way to avoid connecting to the natural gas system is to compress the biomethane (into a compressed or liquefied state) and deliver it directly to the consumption points.

In the case of liquefaction, the freedom of distribution and use can increase significantly, as described above. Distribution can be carried out economically and with considerable flexibility even over longer distances. In addition to supplying fuel for heavy-duty vehicles, it can also be used to power generators operating in island mode or to operate generator parks that balance the electricity grid.

In addition, economic calculations may also result in the implementation of a hybrid system in which a new regasification station similar to the one shown in Figure 6 is added to an existing TSO receiving and compressor station at a favorable cost. (existing) TSO receiving and compressor station with a regasification station similar to the one shown in Figure 6. to receive the produced liquefied biomethane and feed it into the natural gas system. This regasification station can be fed with liquefied gas produced in several biomethane plants, resulting in lower overall (pooled) system investment costs.

An additional advantage may be that the receiving markets (transport, gas network, electricity network) can jointly ensure a higher purchase price for the biomethane plant in the long term and increase sales stability.

Figure 6. Medium-capacity station suitable for storing and regasifying 2 GWh of LNG [14]

With the integrated BioLNG+LCO_2 freezing process, i.e. Carbon Capture & Storage technology, efficient carbon dioxide capture and an additional food-grade carbon dioxide gas can be produced, generating nearly a quarter of the revenue.

LNG, especially when located far from import terminals, can be sold at a significant premium compared to biomethane molecules, primarily to serve the growing fuel needs of transportation and heavy-duty vehicles.

Based on plants with a biogas production range of 500-1000 m3/h, the investment required for a biomethane plant and connection to the network could range from HUF 2.5 to 6.5 billion. In contrast, with BioLNG & CCS technology, the investment could be realized in the range of HUF 2.5-3 billion.

The recommended investment with BioLNG & CCS technology would yield a net profit of HUF 1.4 billion at today's prices, after deducting operating costs. A plant of the same size connected to a natural gas pipeline, after deducting the operating costs of the compressor, can be expected to generate net revenues of HUF 900 million from the sale of molecules and certificates, which may be further reduced by network usage fees.

The total cost of the network connection can only be determined after a precise site survey and study of the surrounding natural gas network, as well as the determination of the pipeline route to be built. This process can significantly prolong the budgeting and preparation phases, and it must also be taken into account that the implementation process will take years. With a single supplier offer for the liquefaction plant, the implementation time can be determined with a high degree of accuracy and can be planned and accounted for.

6. Conclusions

The available funding for biomethane technology developments can hopefully provide a significant boost to the development of domestic biomethane capacities, which are lagging behind in European comparisons. The options for implementing investments include connecting to the natural gas network or, alternatively, liquefying biomethane, even with BioLNG & CCS technology. In the latter case, the avoided carbon dioxide emissions can also result in an additional food-grade product, while the investment costs are at most no higher than the costs of the network connection, while the expected net income can be significantly higher, so the payback period of the investment can be shortened by years.

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