Methane emissions and reduction options for natural gas extraction, transportation, storage, distribution and use

Chapter related to the draft "National Methane Emission Reduction Plan"
as part of the "Cutting methane emissions in Europe and increasing European leadership on methane mitigation (Methane Matters Coalition, MMC)" tender project

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EXECUTIVE SUMMARY

Of all hydrocarbons, methane has the most (four) hydrogen atoms compared to (one) carbon atoms. Accordingly, during the complete combustion of methane, two molecules of water and one molecule of carbon dioxide are formed. In principle, natural gas is one of the cleanest combustion fossil hydrocarbons – from an environmental point[1] of view – with the lowest emissions, and at the same time the lowest carbon dioxide emission energy source today[2].

The environmental and energy efficiency use advantage is not only based on "theoretical chemistry", but there are more efficient and significantly lower emission and energy-efficient thermal power plant technologies available for the oxidation of gaseous hydrocarbons. The pipelines built in the past decades and the liquefied natural gas (LNG) logistics system that can be transported by ship over the past decades from extraction and processing to the user represent a very practical, stable, predictable, safe and sufficiently capacity – very convenient for the customer. In contrast to coal, even despite the nearly 10-fold specific input, the share of natural gas use in the energy mix in Hungary has increased from 22% to 36.8% in the last decade. This trend is stronger than what can be observed worldwide. Natural gas is widely used for heating and electricity generation all over the world as a well-controlled, standby, and available energy source for industrial processes.

This trend is the right direction, especially if natural gas is not used by fossil sources, but from renewable sources! The extraction *(1)*, transport *(2)*, storage *(3),* processing *(4)* and distribution to customers *(5) of natural gas have a very significant impact on the development of the climate*, as this also results in significant methane emissions. Although methane decomposes in the atmosphere much faster than carbon dioxide, it causes a much more significant climate impact in the short and medium term[3]. Reducing methane emissions from the natural gas industry plays a key role in mitigating anthropogenic climate change. Methane also promotes ozone formation through an atmospheric reaction, which causes health and other problems as a secondary air pollutant near the ground. The methane escaping from natural gas into the atmosphere from extraction to use can be as much as 1-4% of the extracted quantity. Methane that we do not extract, use, does not produce harmful substances and does not affect the climate. Therefore, one of the most important is to reduce its use. During the use of natural gas (6th), thermal power engines also emit a significant number of unburned hydrocarbons (TOCs). The specific methane and methane equivalent TOC emissions of households (I.), transport (II.), gas engines (III.), aviation (IV.), as well as industrial (V.) and energy (VI.) gas turbines vary depending on the area of application and performance, but in the flue gas as a whole, up to 0.25-2.5% of the extracted natural gas quantity **burdens** the environment, taking into account that during the combustion of methane, the flow of the gas mass increases[4] 4.99 times We also investigate the indirect weather-influencing effect of harmful emissions.

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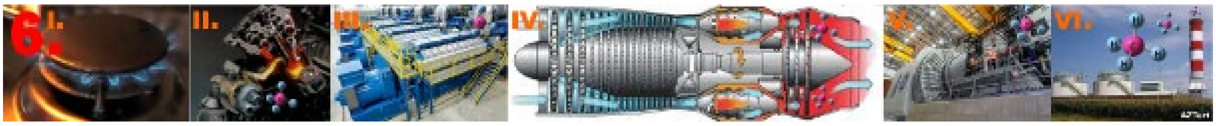
[1] *Compared to coal burning, the specific emissions of energy (PM, NOx, TOC, CO) are up to an order of magnitude lower.*

[2] *E.g.: the specific CO_2 emission of a lignite-fired (coal-fired power plant) energy is up to 1'180 kg/MWh. In comparison, a coupling-axis gas-steam turbine power plant is up to 470 kg/MWh.*

[3] *Methane (CH_4) is a highly potent greenhouse gas that has a much stronger heat retention capacity in the atmosphere than carbon dioxide (CO_2). The concentration of methane is lower than that of carbon dioxide, and when it enters the atmosphere, it is about 80-85 times stronger in 20 years, and about 28-36 times stronger in the next 100 years.*

[4] *The perfect combustion of 1 kg of natural gas (methane) produces 2.25 liters of water and 2.75 kg of carbon dioxide. To give an extreme example: the TOC emissions of a 10 million moped two-stroke internal combustion engine can be over 4'500 ppm. In this case, 2.25 % of the methane equivalent of the fuel used is released unburned into the atmosphere. According to another example, if the TOC emission of a flue gas methane equivalent to methane gas with a mass flow of 1-5 MW four-stroke gas engine generator with a mass flow of flue gas is orders of magnitude higher - fulfilling the regulations in force - then the TOC emission of the methane equivalent to the weight and volume of natural gas used is 0.225 %! Gas turbines have higher TOC emissions. the methane equivalent of the natural gas used can be as high as 0.5-2.3%.*



After **identifying the problem**, let's review the currently available options. The global energy efficiency of thermal power engines is currently 22-35%, and if we could double this value, the methane emissions from thermal power engines can be reduced at the same time by reducing fuel demand. If we were to make the source of methane circular, their use could be climate neutral.

Research Opportunities (7.) for reducing methane emissions. BAT Leak Reduction Technologies:

A. The *use of modern seals* can significantly reduce leaks. Frequent inspection and maintenance of natural gas pipelines and equipment (TMK)[5] is essential. Installed infrared cameras with an automatic alarm system can make the methane leak visible, which is invisible to the naked eye. With ground-based mobile measurements and portable methane detection instruments, pipelines, wells and other gas industry equipment can be manually visited to identify leak points. Methane-sensing infrared camera drones can be used to monitor the entire gas pipeline network. Infra-sensing satellite images make it possible to detect changes in atmospheric methane concentrations. Whether it's in remote or hard-to-reach places. *Rapid elimination of leak points*

B**.** A rapid response service can help eliminate emissions as soon as possible. Rapid *introduction of new technological innovations already known.*

C. Advanced monitoring and alarm systems equipped with intelligent sensors that can continuously detect methane leakage in extraction and processing equipment can be used. The rapid detection of intentional and profit-oriented *methane emissions and the establishment and maintenance of an effective legal, punitive and restorative enforcement system* will help prevent or rapidly eliminate methane emissions**.**

D. *Application of modern flue gas after-treatment systems* used *in and after thermal power engines.*

E. Methane-equivalent emissions of unburned hydrocarbons (TOCs) can be reduced easily and highly efficiently by using oxidative catalysts already known in vehicle technology, so methane emissions can be reduced by one or two orders of magnitude. It is known that catalytic afterburners have a short lifespan, they require special attention and continuous maintenance. Furthermore, its spread on high-performance thermal power engines is also hindered by their very significant exhaust resistance, as it results in a 10-15% reduction in power or a similar amount of additional use of natural gas.

Suggestions (8) to research, develop and introduce further new technical possibilities: *Type adaptation and market introduction of ultra-low exhaust resistance, reliable, long-maintenance-free exhaust gas after-treatment processes (8.1). Research, development and rapid deployment of ultra-low emission catalytic on-bulb and catalytic decarbonisation processes for the conversion and recovery of flare, ventilated and collected leakage methane into marketable commodities, alcohols and gas soot (8.2).Construction of gas-tight, zero-methane-emission, active, autonomous buildings for critical structures of extraction, transport, processing, storage and distribution, from which a mixture of low-concentration methane leakage air – which cannot yet be ignited as a flame – feeds the production of a catalytic over-glow flares (ULE, ZE)[6] heat recovery (8.3). Communal waste and biomass gasification and synthesis gas sharing system.*

To expand the availability of a continuous domestic economical renewable methane source to reduce the demand for fossil and foreign energy-dependent imports (8.4).
The proposals are made in the form of a complex research and development innovation topic outline.

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5 TMK: planned preventive maintenance: planned preventive replacement and maintenance of components.

*6 **ULE:** ultra-low emissions (0-5 mg/Nm^3, **ZE:** zero emissions (0 mg/Nm^3)*

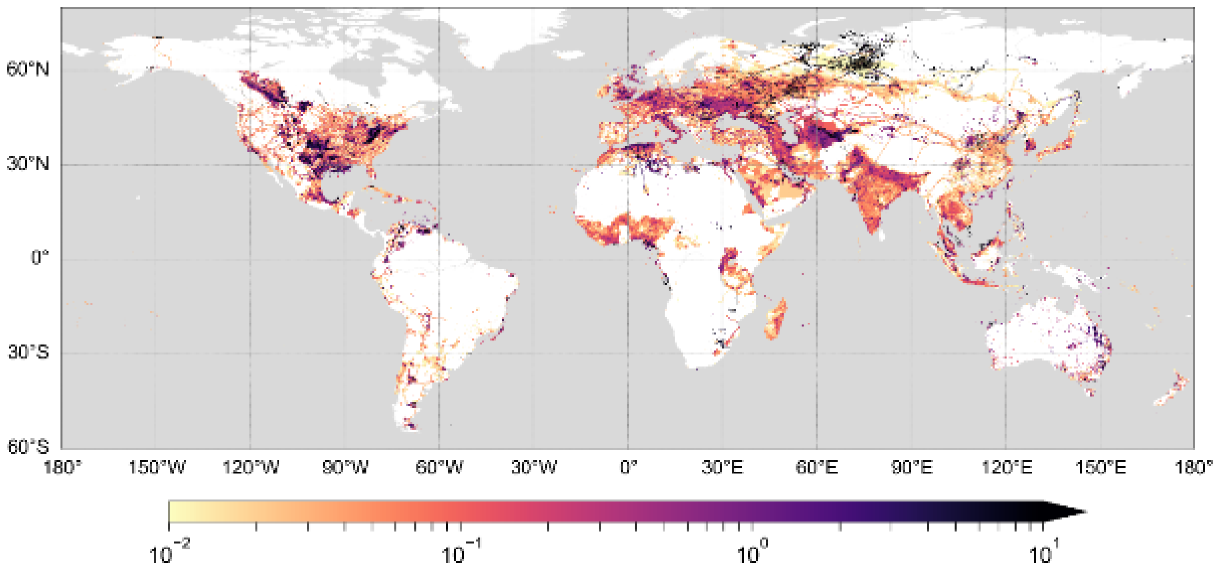
1. Methane emissions associated with natural gas extraction

The vast majority of natural gas is made up of 95-96% methane, and the rest is a flammable gas mixture containing higher-order hydrocarbons. It may also contain ethane, propane, and butane. In addition, so-called inert gases (e.g. CO_2, N_2) are also present. Its density is less than that of air. In its free state, it flows upwards. The 9.page 1. table is also characteristic of Russian natural gas, which is currently dominant in Hungary.

Natural gas extraction is one of the pillars of the modern energy industry, but the process can release significant amounts of methane – an extremely powerful greenhouse gas – into the atmosphere. Reducing methane emissions is key to mitigating climate change, as methane has about 84 times stronger heat retention capacity than carbon dioxide over a 20-year period and 25 times stronger over a 100-year period. The release of methane into the atmosphere is not only environmental but also an economic loss, as the gas escaping could be of significant value to companies if it were properly collected and utilized. To improve the situation, stricter regulations are being introduced around the world, as well as advanced technologies are being used to detect and reduce leaks.

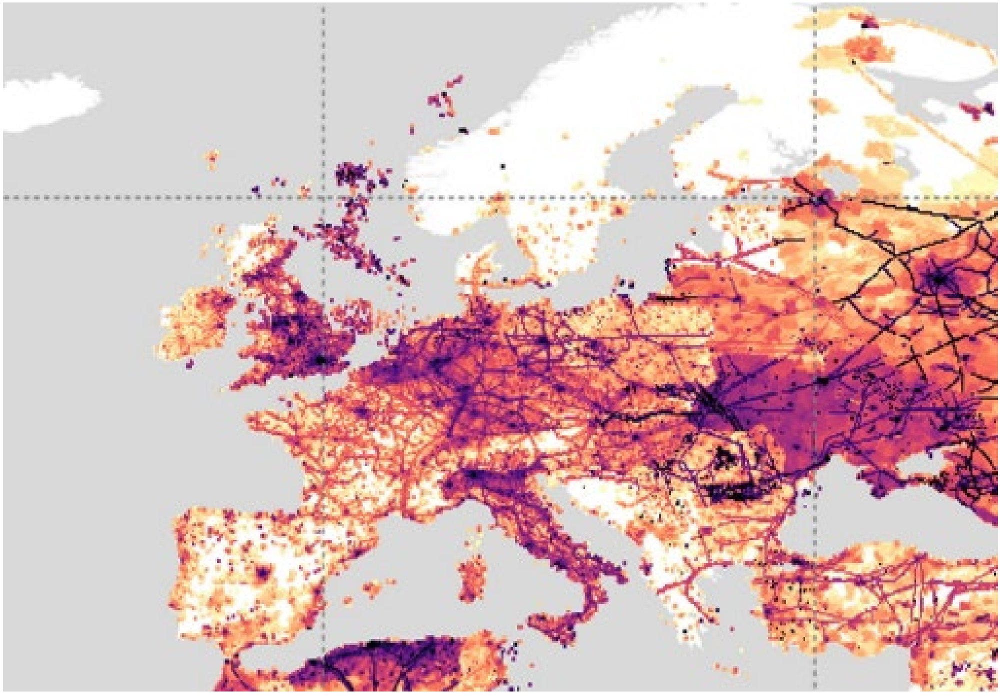
1.1.1. Sources of methane emissions during natural gas extraction

"The world (1. figure) methane emissions, mainly in the northern hemisphere, around fossil fuel extraction and along transport routes." The Earth Observatory has recently published a global map showing the quantities released into the atmosphere during the extraction, storage and transport of fossil fuels. (This amount, by the way, is 97 million tons per year" according to UN data.) That's 7.9 billion tonnes of CO_2[1][2] equivalent to the climate equilibrium equivalent of 19% of total fossil CO_2 emissions in 2024. The map was created with the help of NASA's Carbon Monitoring System and shows the source of methane not only by country, but also traced back to the exact location of the release. This means that we can see the locations of pipelines, (the coal mines), the oil and gas wells or even the refineries on the map. These data can then be compared with satellite measurements to see exactly where we need to do and where the measures we have already taken have been successful."[2]

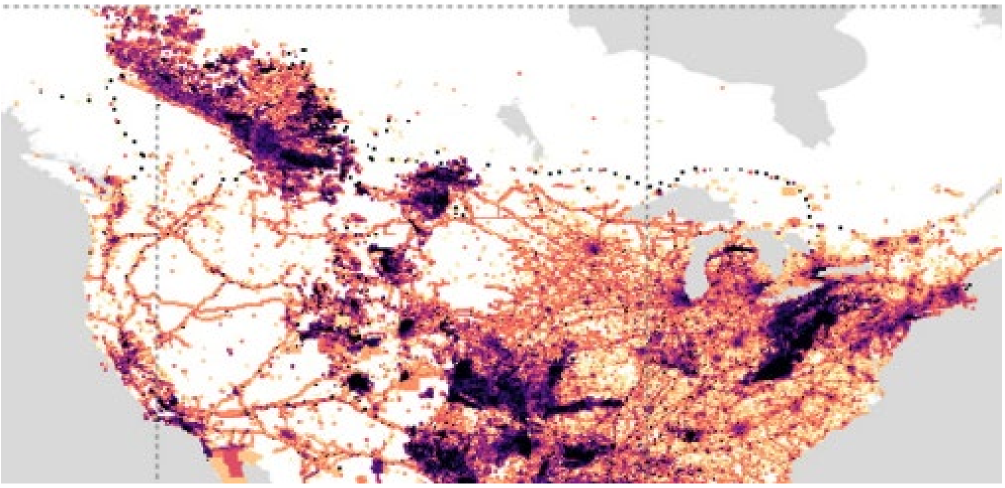


1. Figure: Distribution of methane emissions in the world [2]

"The map reveals details such that the largest oil-related emissions come from Russia, the US leads the natural gas-related emissions, and the coal-related emissions are the most significant in China. On the map, we can see the natural gas pipelines as dark lines, but the emissions are not uniform over the entire pipeline section, but can be linked to the compressor stations, which follow each other every few hundred kilometers. (Since the pressure of the gas in the pipeline is constantly decreasing due to friction, the pressure must be increased again and again, for which compressors are needed.) While in Canada a series of dots indicate the pipelines, as these are only the compressor stations themselves, in Russia the network had to be digitized based on paper maps, but these do not indicate where the stations are located at all. There are several satellites that measure various atmospheric gases, such as the Japanese GOSAT, the European TROPOMI, and their data have already shown, for example, that both the US and Canada underestimated the amount associated with fossil fuels, while the Russian and Chinese emissions were overestimated. This may be due to uncertain or incomplete local measurement data."[3]

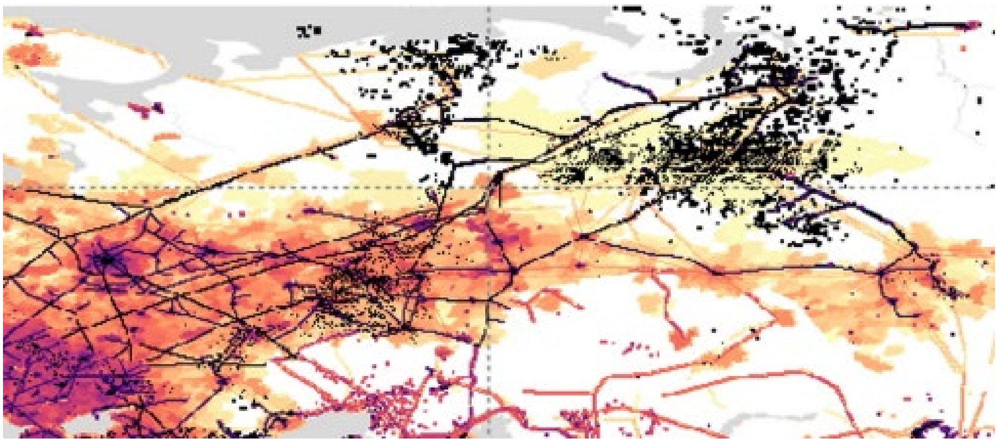


2. Figure: Distribution of methane emissions in Europe [1]



3. *Figure: Distribution of methane emissions in Canada[7] [1]*

[7] In Canada, it is indicated by dots, as it is known here where the compressor stations that are active in leaks are.



4. Figure: Distribution of methane emissions in Russia[8] [1]

- **Drilling and operation of wells:** When natural gas wells are drilled or operated, some of the methane released from underground can be released directly into the atmosphere. During the drilling and operation of natural gas wells, it is a common phenomenon that methane found in the depths of the earth is released. This methane is not always fully captured or utilized, so some of it may be released directly into the atmosphere. For example, methane can be released during drilling when the well is led into the deeper layers of the earth's crust and the gas flows towards the surface due to the pressure difference. During operation, leaks can occur in the processes of extraction, transport and processing, which can release methane into the atmosphere. Even a small leak can become a bigger environmental problem if we do not pay proper attention to prevention.
- **Flaring and venting:** When some of the gas extracted cannot be used or is burned for safety reasons (flaring) or released (ventilation), a significant amount of methane can escape. This is how often it occurs during gas extraction. During flaring, surplus or unusable natural gas is burned on an open flame, usually for safety or technological reasons. This prevents gas from escaping into the open air, which can pose a risk of explosion or health. The combustible substance content of vented gases is sometimes so low that it cannot be ignited with a conventional flame; In this case, the use of catalytic bulbs is recommended.

5. Figure: Torching [4]

[8] In Russia, too, there is a leak in the vicinity of compressor stations

Although most of the methane is converted into carbon dioxide, the process is not perfect: unburned methane molecules remain during flaring, especially if the combustion is incomplete. During ventilation, part of the extracted gas is released directly into the atmosphere, mostly for technological or safety reasons. This method involves the emission of particularly large amounts of methane, since the gas is released into the air without combustion. As a result, the environmental impact of ventilation is generally less favourable than that of flaring.

- **Fugitive emissions:** Methane can leak continuously through tiny cracks and leaks in pipelines, valves, compressors, and other equipment used to transport and store natural gas. Leaks are gas emissions that are released into the environment uncontrolled, often undetected, from industrial equipment, mainly from the infrastructure used to transport and store natural gas.
  Overall, seemingly insignificant leaks represent a significant environmental burden. The network of natural gas equipment is very extensive, and leaks often occur through microscopic cracks and sealing defects.
  Such places are difficult to discover, so regular inspections, state-of-the-art sensors and maintenance are required.
- **Maintenance and repair work:** Even during regular maintenance, equipment may release methane, such as when draining pipelines and during transport and storage. Leaks from natural gas transmission and storage systems are a significant environmental challenge. Therefore, regular inspections, the use of advanced technologies and conscious maintenance are necessary.

1.1.2. Environmental Impacts

While a leak may seem small on its own, global aggregate emissions are a major contributor to global warming. Methane not only warms the atmosphere, but also contributes to air pollution and ozone formation, which carries health risks.

1.1.3. Options for reducing emissions

1. **Leak Detection and Repair (LDAR):** Traditionally, leak detection has been a time-consuming and labor-intensive process, often relying on visual inspection and the use of handheld instruments. With modern technologies, such as infrared cameras or drones, methane leaks can be detected faster and more efficiently, so they can be repaired in time. Leak Detection and Repair (LDAR) methods have undergone significant development in recent years, thanks to the use of modern technologies such as infrared cameras and drones.

6. Figure: Accurate leak location detection with direct methane gas detection [4]

Infrared (IR) cameras are able to make methane leaks visible that are not detectable to the naked eye.

7. Figure: Infra (OPGAL EyeGAS) VOC handheld camera methane leak detection [4]

8. Figure: Methane detection sensors can be purchased cheaply in a wide range of products: they cost 4-5 €/piece, they could even be a mandatory standard part of pipe connections and fittings. [5]

9. Figure: Opgal EyeCGAS image processing and data transfer device [4]

10. Figure: By installing LDAR cameras on drones and collecting remote data, leak detection can be organized on a regular basis, even in the entire extent of natural gas pipelines [4]

These cameras allow for quick inspections, even in large industrial facilities, so the detection of defects is significantly faster and more accurate. IR technology is like "looking for a needle in a haystack", only much more efficiently. In addition, for example, Opgal EyeCSite™ enables the quantification of VOC emissions based on image processing with its proprietary software. Detection and measurement give methane equivalents, but the actual composition of natural gas may differ.[6]

Main components of natural gas %	
Methane (CH_4)	95,822
Ethane (C_2H_6)	2,331
Propane (C_3H_8)	0,716
Butane (C_4H_{10})	0,216
Nitrogen (N_2)	0,678
Carbon dioxide (CO_2)	0,194

1. Table: Typical natural gas composition in Hungary [7]

Equipment upgrades: *The use of new, better-sealed valves, compressors, and piping can significantly reduce leaks.*

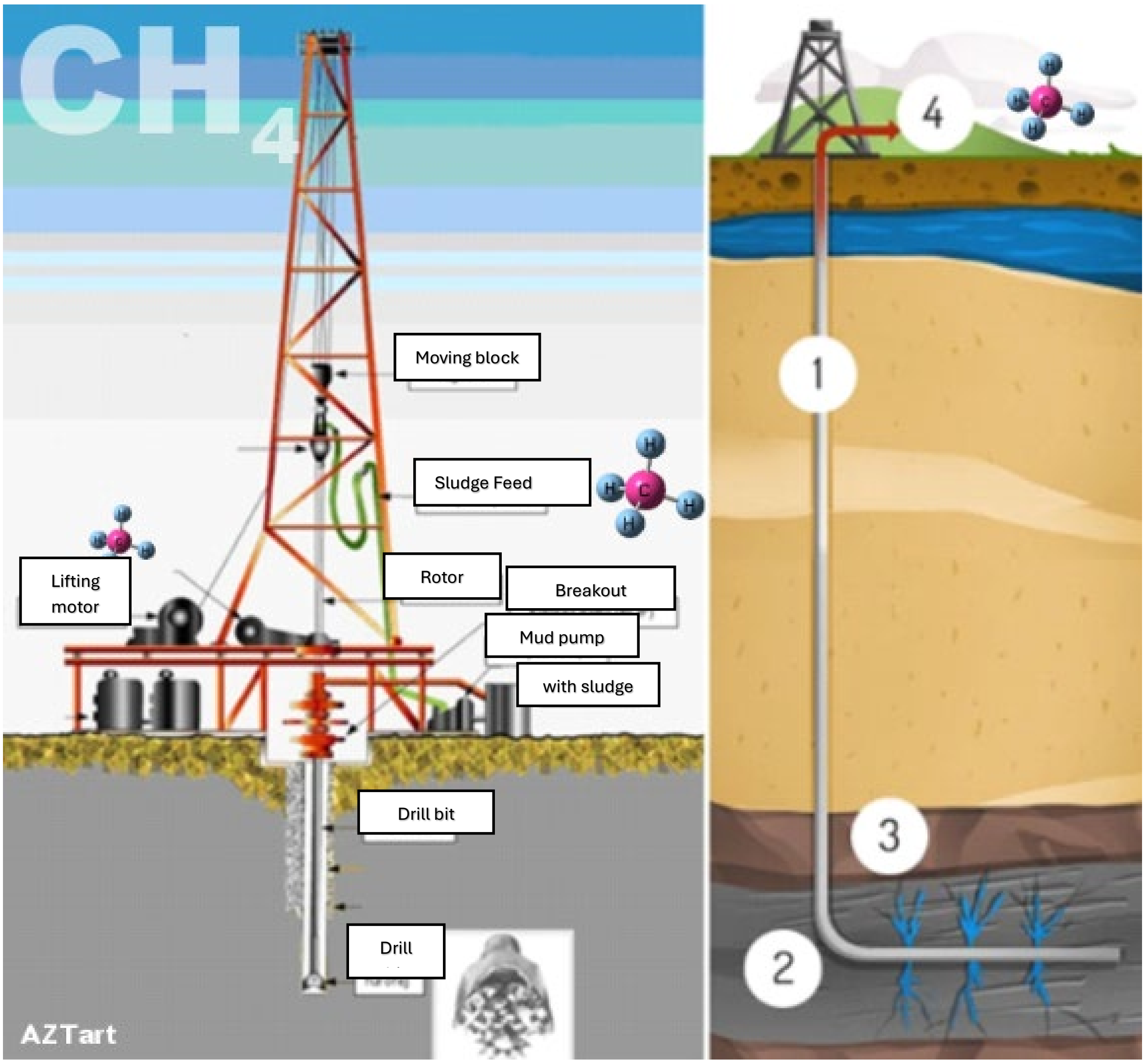
11. Figure: All pipe connections and fittings can be a source of methane leakage. [4]

2. **Minimizing untreated flaring and ventilation:** Technological advances are making more natural gas available for recovery, so less is burned or released.
3. **Digital monitoring systems:** Automated systems continuously monitor equipment and immediately notify you if abnormal methane emissions occur.

1.1.4. International regulation and domestic efforts

Stricter environmental regulations are coming into force throughout Europe – including Hungary – to curb methane emissions. For example, the European Union's Methane Strategy program has set the goal of standardizing the measurement, reporting and reduction of methane emissions. In Hungary, companies in the natural gas sector are also placing more emphasis on the use of transparent monitoring and the best available leakage reduction technologies. Still, when random checks are carried out, 8 out of 10 measurements of methane leaks at Hungarian fossil industrial sites showed very significant data. [8]*James Turitto*, the researcher who took the photos and measurements commented on the results: *"I was surprised to see methane emissions and leaks at almost every site I visited. This means that we don't really know how much more methane Hungary emits than officially admitted."*[9]Tackling the problem requires complex technical, legal and economic steps, but technological advances and stricter regulations are increasingly effective in reducing emissions. If all actors work together, the desired result can be achieved together. Any train with a potential leakage with a mandatory sensor and a remotely accessible monitoring system set up at the sites could provide at least an accurate picture of emissions and the imposition of mandatory technical measures.

1.2. Generation of natural gas, environmental and climate impact characteristics



12. Figure: Conventional rotary drilling rig and shale gas extraction process [4, 10]

LEFT: Traditional "rotary" drilling rig. **Right:** Process of shale gas extraction: **1.** Drilling vertically and then horizontally deep into the rock (3-7 km in Europe) **2.** At high pressure, fracturing fluid is injected into the hole (containing fresh water, granular material such as sand and chemical additives, including benzene and formaldehyde, which are highly carcinogenic), which cracks the rock. **3**. Through the cracks, the gas is forced out into the borehole, and from there into the well shaft and onto the surface. **4.** The fracturing fluid (flowback) contaminated by materials present in the rock, e.g. heavy metals, is returned to the surface. Here, most of the liquid is recycled for new cracking after more or less treatment; What you don't have to be stored. According to international calculations, 25-90% of the used liquid remains underground.

The production of natural gas began millions of years ago, in the geological past, when dead plant and animal remains gradually decomposed under thick layers of sediment, in an environment cut off from oxygen. This process, called anaerobic degradation, took place over millions of years under the combined effect of temperature, pressure, and the geological time scale. Based on the deposit, natural gas can be classified into conventional and non-conventional categories. While fossil fuels in the former category are readily available, in the latter case they can be found at deeper depths (at least 4500 meters), often in places that are difficult to extract.

Natural gas can be extracted using a variety of methods, and the technology chosen depends largely on the characteristics of the deposit. In the following, we will present in detail what solutions are available for the extraction of natural gas. Gas from organic matter is collected in porous rocks, so-called reservoirs, and there is usually a sealing rock layer above them that prevents the leakage of natural gas. Natural gas deposits often occur in combination with petroleum, but they can also be found independently. The extraction of oil and natural gas is an extremely complex process that involves very serious technical challenges. Extraction usually begins with the drilling of a test well, which confirms that there is enough natural gas at the site and its extraction is cost-effective. Only after successful test drilling will the infrastructure for production be built.[10]

Surface effects: The construction of natural gas wells, pipelines and other infrastructure at the extraction site interferes with the landscape, can lead to habitat loss, soil and water pollution if not properly managed.

1.3. Natural gas consumption in Hungary in the light of international trends

Natural gas as an energy carrier has played a key role in the world's energy supply for decades, including in Hungary. However, in recent years, significant changes have been observed in both domestic and international natural gas consumption trends. The aim of the analysis is to present how Hungary's natural gas consumption fits into global processes, what factors influence domestic consumption, and what future prospects we can expect.

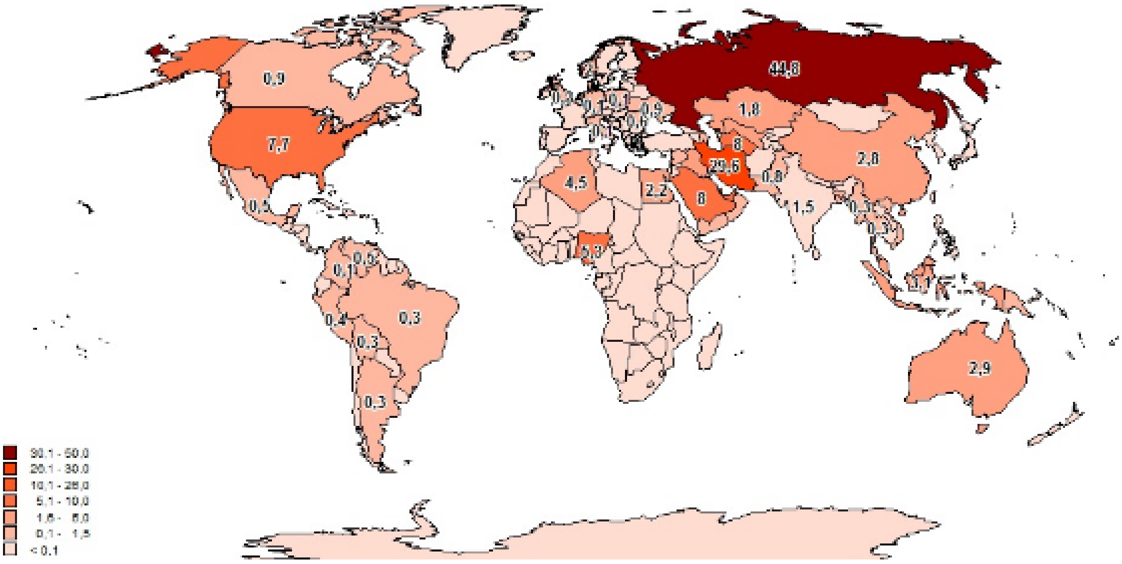
International natural gas consumption trends

In recent decades, natural gas has become the world's second largest source of energy, primarily due to its cleaner combustion than coal and its flexible use.

On a global level, the increase in natural gas consumption was mainly significant in Asia, especially in China and India, where both energy demand and environmental considerations drove the transition.

However, in recent years, due to climate protection efforts, energy efficiency measures and the spread of renewable energy sources, the increase in demand for natural gas has moderated, and even stagnation or decline can be experienced in Europe and North America. The Russian

Ukrainian conflict and the efforts to diversify European energy supplies have also had a significant impact on international natural gas markets.



13. Figure: Natural gas deposits and their distribution in the world (thousand billion Nm^3) [11]

Changes in natural gas consumption in Hungary

Natural gas is a key focus in Hungary's energy consumption – it also plays a significant role in domestic heating, electricity generation and industrial use.

Since the change of regime, natural gas consumption has shown a fluctuating picture: in the early 2000s, there was an increase, then in the 2010s a gradual decrease, which was mainly influenced by energy efficiency measures, insulation programs, as well as the reduction of utility bills and economic crisis.

In recent years, natural gas consumption in Hungary has shown an upward trend again, partly due to economic growth and partly due to energy transition processes. Natural gas remains the most common heating method in households, while gas-based power plants play an important role in industry and energy production, especially in balancing weather-dependent production of renewable energy sources.

Hungary's position in relation to international trends

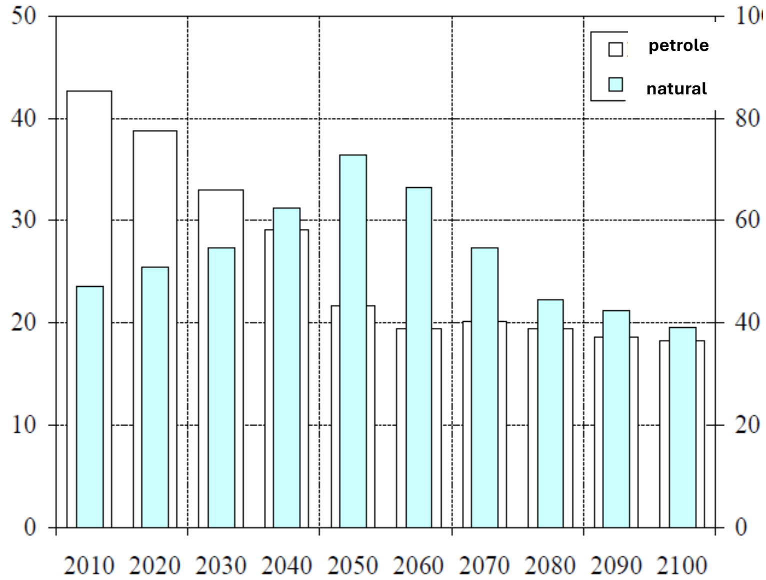
Hungary's natural gas consumption is in line with Central European trends, but at the same time the country is heavily exposed to imports, especially Russian natural gas. In order to ensure the security of energy supply, efforts to diversify sources have come to the force in recent years, such as access to LNG terminals and the construction of new interconnectors.

In line with its climate protection commitments, Hungary is also striving to reduce the share of natural gas in the overall energy mix, mainly through renewable energy sources and increasing energy efficiency. At the same time, natural gas continues to play an important role as a transitional energy source in replacing coal-based energy production.

Future prospects and challenges

In the coming years, the development of natural gas consumption in Hungary will be influenced by a number of factors: fluctuations in international prices, security of energy supply, the spread of renewable energy sources, and residential and industrial energy efficiency investments.

Policymakers need to consider both immediate and long-term aspects during the energy transition.



14. Figure: The world's expected oil (x 109 tons) and natural gas (x10^{12} Nm^3 production) [7]

Based on international trends, it is expected that the role of natural gas will decline in the longer term, but it will continue to be indispensable in energy supply in the short and medium term. Security of supply, diversification of sources and the harmonization of sustainability goals remain key for Hungary.

Hungary's natural gas consumption is closely aligned with regional and global trends, but it also faces unique challenges due to the country's geographical and economic characteristics and the structure of its energy supply. The success of the energy transition depends on how Hungary is able to combine international experience with domestic opportunities, keeping in mind economic, environmental and social aspects.

1.4. Natural gas extraction sites in Hungary

Hungary's geographical location and geological conditions have made it possible for the country to have significant natural gas deposits. The extraction of natural gas is an important pillar of domestic energy supply, which has been providing the necessary energy carrier for the population and industry for decades. In 2024**, domestic production was about 1.4 billion Nm^3** (normal cubic meters), and according to optimistic (Copilot) estimates, 1.9 billion Nm^3 of natural gas is expected to be produced in 2025.

1.4.1. History of natural gas deposits in Hungary

The first significant natural gas deposits were discovered in the 1900s in Hungary, in the Great Plain. After the Second World War, the rate of extraction accelerated and reached its peak in the seventies and eighties. Nowadays, domestic production covers about 15-20% of consumption, the rest must be replaced by imports. The history of Hungary's natural gas deposits is closely intertwined with the country's industrial development, economic transformations and energy security efforts. Although natural gas was hidden in the depths of the Carpathian Basin for thousands of years, it became one of the country's most important energy sources in the 20th century.

Below we will review the main stages of this story, from the discovery of the most significant deposits through the periods of extraction to the present day. The first signs of natural gas bursts appeared as early as the end of the 19th century, mainly in the Southern Great Plain region. Peasants and herders often experienced "burning water" or "earth fire" caused by gas gushing from the ground. For a long time, these phenomena were explained by superstitions, while scientific interest was first directed to them at the turn of the century.

Boom in hydrocarbon exploration (first half of the 20th century)

At the beginning of the 1900s, systematic geological explorations began, during which they mainly searched for crude oil, but often natural gas was also found. The first significant natural gas deposit was discovered in 1915 in Hajdúszoboszló, although at that time extraction had not yet started on an industrial scale. In the 1930s, oil exploration gained momentum, and as a by-product, more and more natural gas deposits were discovered. During the Second World War, the energy shortage increased the importance of domestic deposits. The World War did not remain ineffective for the oil industry either: in addition to the strong increase in production, it also brought about changes in quality. The oil industry was the most rapidly developing industry at that time. By 1943, the crude oil processing capacity had almost tripled compared to 1930 (from 280,000 tons to 805,000 tons per year) and was divided between 14 factories. Hungary's crude oil production reached 837,711 tons in 1943, but this was practically produced by MAORT's petroleum production plants in Zala County. In the same year, the factory site of the Hungarian Oil Works Co. in Szőny was established. The number of hydrocarbon mining companies and the capital invested were increased by the establishment of MANÁT (Hungarian-German Mineral Oil Works Co.), MOLÁRT (Hungarian-Italian Petroleum Co.) and ONÁRT (Italian-German Prekmurje Mineral Oil Co. Ltd.).[12]

With its borehole No. 2 in Budafapuszta, EUROGASCO put into production a field that provided the country with the opportunity to cover its growing oil needs from its own resources. The operation of MAORT has been followed by special attention since its foundation.

Thanks to its invested share capital and lively development, it has risen to the ranks of the country's large companies in the first years of its existence. By the years 1941-42, the entire Hungarian organization of MAORT had essentially been formed. At the time of the commissioning of the Treasury on 20 December 1941, the following plants were listed: the Bázakerettye plant, the Lovász plant, the Lendvaújfalu field, the Hahót exploration well No. 5, the oil transmission line on the Lovászi-Kerettye-Budapest line, the filling stations in Újudvar, Kápolnásnyék, Soroksár, Mihályi-1. No. 1 deep drilling with the dry ice plant, deep drilling No. 1 in Inke, as well as geological and geophysical exploration in the concession area.

English and American companies

The state of war with England and the United States adversely affected Anglo-Saxon companies. In December 1941, the plants of Shell Petroleum Co., Vacuum Oil Co. and MAORT were taken into the use of the treasury and put into the service of the war economy.

The Golden Age of Industrial Extraction and Natural Gas (1950–1990)

After the Second World War, from the 1950s, the production of natural gas on an industrial scale began in Hungary. During this period, the most significant deposits were discovered and exploited:

Hajdúszoboszló: The largest natural gas field in the country, the production of which started in 1957 and soon provided the backbone of the Hungarian energy supply.

Algyő: The Algyő field, which was discovered in the 1960s, became of key importance for both natural gas and oil reserves.

Szeged area: A few smaller and larger deposits have been discovered in the Southern Great Plain, which have contributed to the diversification of domestic gas supply.

Socialist industrialization policy placed significant emphasis on the exploitation of domestic energy resources, so the construction of the natural gas pipeline network, residential gasification and industrial use also developed at a rapid pace.

The Import Era and the Significance of Domestic Stocks

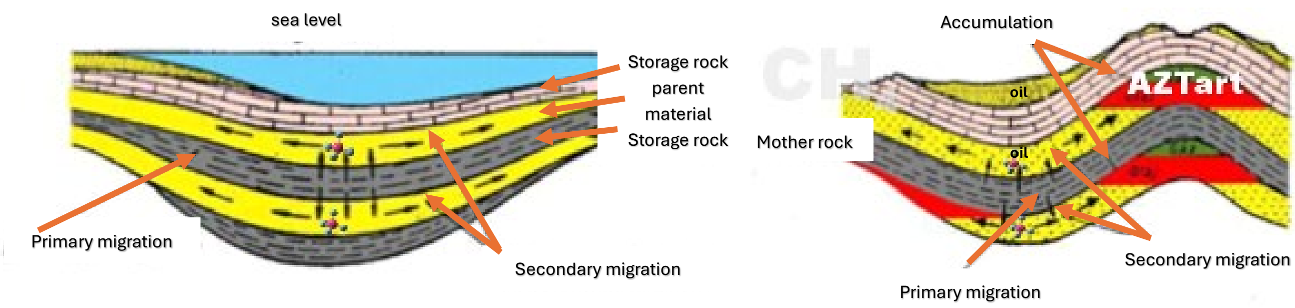
After the change of regime, Hungary increasingly reliant on imported natural gas, mainly from Russia, as the production of domestic fields gradually decreased. However, existing reserves, although dwindling, continue to play an important role in the country's energy supply, especially in times of crisis. In recent decades, research has moved towards deeper layers, and the focus has also been on alternative energy sources. Thus, Hungarian natural gas deposits are now valuable not only from an energy point of view, but also from a strategic and economic security point of view. They have stopped operating more than 600 stations in the past decades. With every natural gas extraction, not only methane, but also carbon dioxide and other polluting gases come to the surface. In addition to gas extraction, smaller amounts of crude oil and not insignificant amounts of mine water highly saturated with salt also come to the surface.

The extraction of a natural gas well is stopped when the volume of production decreases and the increase in pressure reserved for increasing extraction is no longer economical, or the carbon dioxide content of the extracted raw mine gas reaches or exceeds 30%, or the disposal of mining wastewater or the increase in processing costs make extraction uneconomical.

The gas price fluctuations and gradual and sustained average price increases of recent years encourage gas producers to review the economic feasibility of reopening some (low gas) wells. Other deeper areas are known, and there are shale gas fields in Hungary as well, which have been attempted to be explored, but their extraction can be maintained at a significantly higher cost. Even with the increased natural gas purchase prices, it is difficult to imagine that shale gas extraction in Hungary can be considered economical. [13]

The Makó Trench contains two parts:

- Makó shallow-depth trench, which targets traditional sandy waters at depths between 2300 m and 3500 m,
- The deep extraction trench in Makó targets significant non-conventional, contingent resources below 4000 meters.



15. Figure: Formation of gas storage layer formations in several migration passes in a time interval of 100 million years [13]

Extensive AVO (amplitude-offset) seismic analysis of the Makó shallow deposit identified several gas deposits, and 3D seismic data revealed the presence of possible gas zones in the Algyő Formation.

The Makó Deep Deposit is not a traditional deposit, focusing on the accumulation of shale gas and oil (Endrődi Formation) and narrow gas (Szolnok Formation) found in low-permeability and low-porosity rocks in the central parts of the trough. [13]

In order to reduce the vulnerability to foreign energy sources, e.g. natural gas, it is not only possible to do something in the interest of the national economy by exploring new natural gas fields and drilling new wells, but the "lean-natural gas" wells that have already been withdrawn from cultivation can be utilized by catalytic heat release with an efficiently oxidizing catalytic incandescent chamber even with a carbon dioxide content of over 30%.

It can be produced even from mine gases well below the ignition concentration (with ultra-low or zero pollutants and low CO_2 emissions), heat, electricity, and can be powered by thermal power engines (8.2 chapter, the 53. page).

This technical possibility would allow the processing of lean natural gas equivalent to about 500-600 million Nm^3.

If the catalytic incandescent heat release is able to heat all the CO_2 and water vapor content already present in the mine gas and produced during the combustion of methane to the catalytic decarbonization temperature by utilizing the flue gas, then it is possible to convert the entire amount of carbon dioxide into alcohols and oxygen, while significant water vapor remains in the flue gas.

Almost all industrial and communal consumers are available on the natural gas transmission and distribution network built and maintained in recent decades.

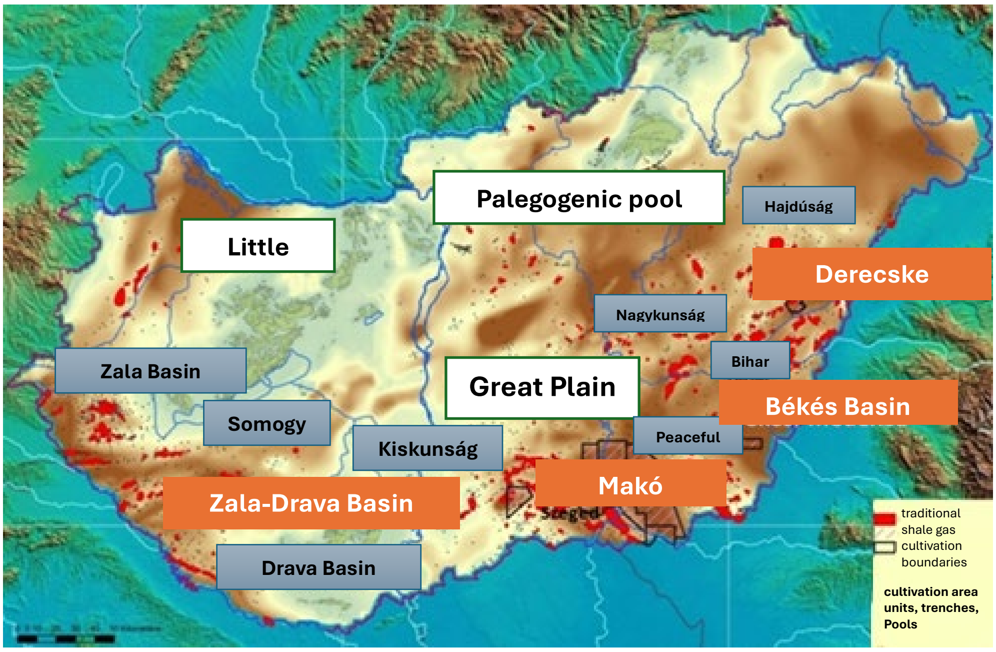
Through these pipelines, natural gas can not only be delivered to customers, but syngas can also be collected from communal industrial waste, sewage sludge, slurry, agricultural by-products, wood chips, and even from leaves collected in gardens and parks during catalytic rotojet gasification.

Where the waste is generated, we do not transport waste, but we share and store the syngas on the former natural gas network.

By catalytically converting the significant amount of hydrogen and carbon monoxide released during the process into methane, as well as by efficiently separating solid ash from dust, sulphur and halogen compounds and converting them into useful materials, up to 16 billion Nm^3 of circular syngas can be produced in Hungary, but with the equivalent of natural gas energy, which is significantly lower at cost.

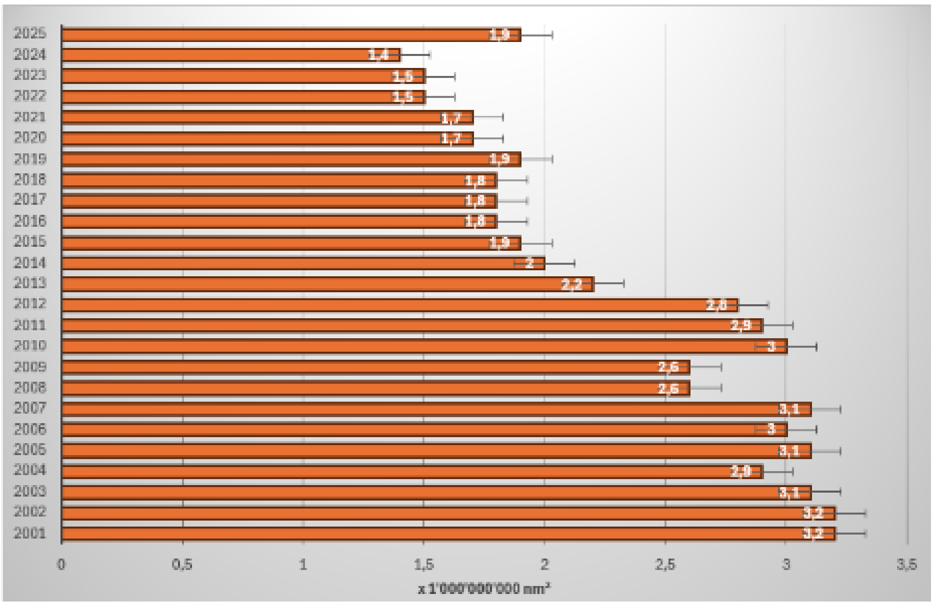
The "re-methane" fields of the future are not to be found underground, but in the field of waste recycling (8.4 chapter, the 57.page).

1.5. Current main natural gas extraction sites in Hungary



16. Figure: Hydrocarbon deposits in Hungary [11]

16. Figure: Hydrocarbon deposits in Hungary Shows Natural gas deposits in Hungary. From the 17. Figure: Natural gas production in Hungary 2001-2025 the development of domestic natural gas production can be seen from 2020 to the present day. The year 2025 is characterized by a hopeful expected value. In order to reduce Hungary's dependence on natural gas imports and its vulnerability, there are very serious government efforts and incentives to increase domestic natural gas production to over 1.9 billion Nm^3. Investments are also supported by the fluctuating, slow upward trend of international natural gas prices.

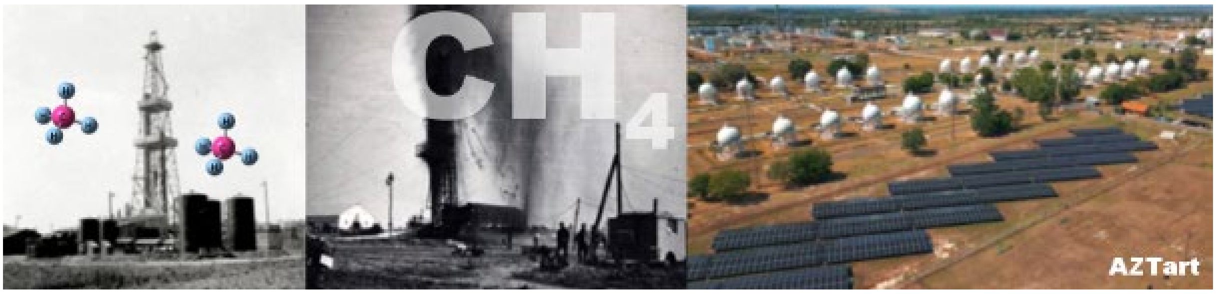


17. Figure: Natural gas production in Hungary 2001-2025 [11]

The so-called lean natural gas deposits with a high carbon dioxide content of up to 30% have the potential to extract at least 500-600 million Nm^3/year of natural gas.

The estimated volume flow of leaking methane for this quota is 50–62.5 million Nm^3!

1.5.1. Algyő - Makó



18. Figure: Gas production in Algyő: from the beginnings to today [12] [4]

The country's largest and most well-known natural gas field is located near Szeged. It was discovered in the 1960s and still produces a significant amount of natural gas to this day. The field of Algyő supplies not only natural gas, but also crude oil.

In 1965, 60 years ago, oil and natural gas extraction began in Algyő, which is still unavoidable in the domestic energy supply.

The significance of the Algyő site remains unchanged, but its role is gradually changing in the spirit of sustainability and energy transition: in addition to hydrocarbon extraction, renewable energy production and storage are gaining more and more emphasis.

In the summer of 1965, researchers found crude oil at a relatively shallow depth of 2200 meters and discovered one of the most important oil and natural gas fields in Hungary.

Six decades have passed since the internationally significant discovery, during which time the Algyő deposit proved to be the strongest and most stable pillar of the security of supply in Hungary, with almost 1000 hydrocarbon wells drilled in the field over the years.

Although the known reserves are dwindling, the significance of Algyő remains unchanged, as the field currently provides a tenth of the country's total natural gas consumption and five percent of its crude oil consumption. In the eighties, at the peak of production, this proportion reached 70%.

In addition to its role in strengthening energy self-sufficiency and reducing import dependence, the Algyő site has also performed outstandingly in terms of employment: since the beginning of production, it has provided stable jobs for thousands of workers throughout their careers.

Thanks to the knowledge and innovation capacity accumulated here, Algyő has become the center of the technological development of the Hungarian oil and gas industry, and several modern production solutions were first applied here.

The experiences of Algyő greatly contributed to the strengthening of the Hungarian hydrocarbon extraction traditions and to the education of generations of professionals.

Over the past 60 years, 280 million barrels of crude oil and 82.5 billion cubic meters of natural gas have been extracted in Algyő, which means a total equivalent of 800 million barrels (to illustrate the proportions: 550 million average passenger cars could be filled with refined fuel from 280 million barrels of crude oil, and 82.5 billion cubic meters of gas would be enough to supply all domestic households heated with gas for twenty years).

However, MOL's Algyő site is much more than hydrocarbon production and its infrastructure: MOL's exploration and production division works closely with other areas of the company. There is a logistics site, a laboratory, a fire brigade, and the production of gas products takes place here.

MOL's maintenance service company and the country's strategic gas storage facility are also located here. In addition, Algyő also receives and processes the products of other oil companies in the area. The site still employs almost 800 people.

"*Algyő is a true symbol of the Hungarian energy supply: it embodies our exploration and extraction traditions, the dedication and expertise of our predecessors and today's colleagues, as well as the opportunities inherent in the energy transition and sustainable energy use.*

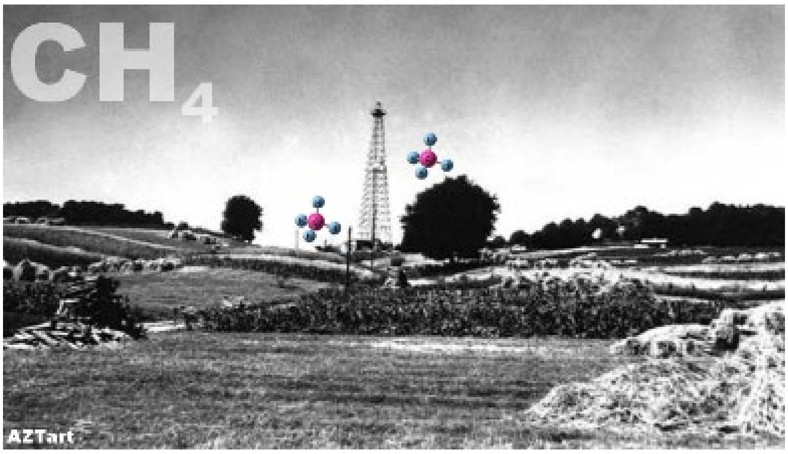
We are proud of the fact that we have played a key role in the country's security of supply over the past six decades and we are committed to ensuring that Algyő continues to play a significant role in the energy industry of the future," said József Molnár, CEO of MOL Group.

One of the key elements of MOL Group's long-term SHAPE TOMORROW strategy is the smart green transition, for the implementation of which increasing the share of renewable energy sources in addition to fossil fuels is key.

In this spirit, MOL will build a 37.4 MWp solar park and a related electricity storage system with an energy storage capacity of 40 MWh at its site in Algyő. The investment will enable the independence of the MOL facilities in Algyő from grid electricity, significantly improve the flexibility of electricity supply and reduce CO_2 emissions from the site by 13,000 tons per year." [12]

The burning of 82.5 billion Nm^3 of gas over the past 60 years translates to 223 million tonnes of carbon dioxide and up to 2.1 billion Nm^3 of leaked methane gas, equivalent to an additional 476 million tonnes of carbon dioxide equivalent that distorts the climate balance."

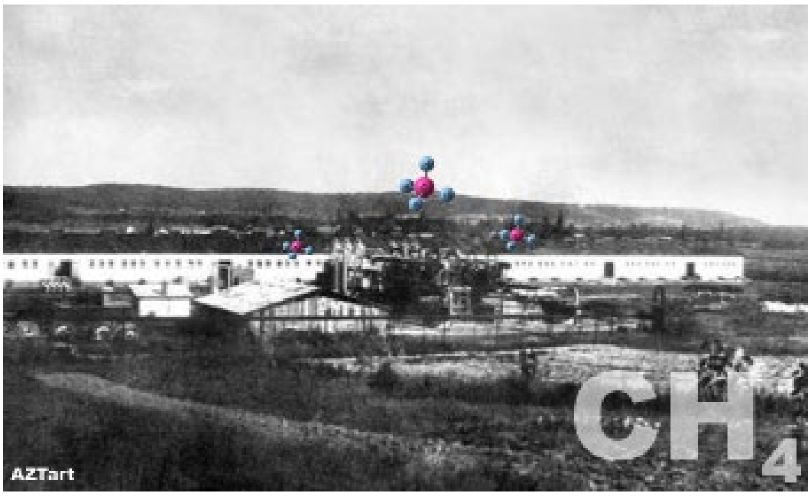
1.5.2. Lovászi



19. Figure: Deepening of the L1 well in July 1940 (photos by Simon Papp) [15] [4]

In the industrial history overview of the oil and gas fields of Lovász, almost all methane emission events, quantities and consequences can be analyzed based on the quotations compiled below.
"In the autumn of 1937, Hungarian oil mining was born in Zala, and less than a year later, in the summer of 1938, the first large Hungarian hydrocarbon mining company, the Hungarian American Oil Industry Company (MAORT), was established (with full American capital) to produce the

discovered oil field and continue further exploration. The company name, which is usually only used in abbreviated form, soon became a concept. The oil and natural gas produced by MAORT became a decisive factor in the development of the economy (the company's production already covered the entire domestic demand in 1940), a backward region began to develop, and the opportunity for a livelihood and a better life was created for thousands of people. The first exploration drilling began on 6 June 1940 with the R-2 steam-powered rotary equipment at the borehole designated by geologist Dr. Simon Papp in the Lovász vault. Their drillers were Béla Horváth, János Csörgits and István Vangyia. It took from June 6 to August 17, 1940, to reach a depth of 1566 meters. The examination of the drilled layers was started by the drilling rig No. R-2, then continued by the Cardwell hole finishing rig relocated from Budafapuszta under the direction of drill master József Schlosser, Sándor Nagy and József Fejér. After perforating the sections between 1468 and 1452 and 1442 meters (piercing the liner pipe securing the borehole to allow hydrocarbons to flow into the well), the well-produced gas and oil. At the opening of the section between 1302 and 1318 meters, the well showed signs of eruption, and the danger could only be averted with several days of strenuous work. The production of the well had been included in the reports since the completion of the drilling, but its regular production only began after the completion of the investigations, on 1 December 1940. During the trial production, they received 62 thousand cubic meters of gas per day through a ten-millimeter nozzle."



20. Figure: Lovászi [15] [4]

"After the successful drilling, the exploration of the field began at a rapid pace, and by the end of the year, three wells were already in production. During the next year – that is, until December 1941 – 22 wells were deepened in Lovászi, and all of them were successfully trained to be producers. In the oil field of Lovász, the mining plots were registered under the protection name "Simon" after the first name of the first drill point marker (dr. Simon Papp).

The geological structure outlined from the data of the boreholes, the Lovász oil field, is an elliptical vault of about twenty square kilometers in size in an east-west direction on the border of the villages of Lovászi, Kútfej and Tormafölde. Some of the layers containing oil and natural gas extend to the territory of Slovenia at a distance of one to one and a half kilometers in the west. Oil and natural gas storage facilities are layers of sand and sandstone separated by layers of marl of different thicknesses.

The five hydrocarbon storage layers of the Lower Pannonian age, located at a depth of one thousand to fifteen hundred meters, were named after the surrounding villages as the Páka, Sziget, Rátka, Lovászi and Kútfej levels. Among them, the Rátka and Lovászi sandstone series stored the largest oil and natural gas reserves. The production of the L-1 well also started from these. The displacement energy was provided by the gas cap formed over the oil deposits, the pressure of the dissolved gas and, to a lesser extent, the flow of the water at the edge."

"MAORT, which discovered the oil field in Lovász, carried out the exploration of the field and the construction of the plant at a rapid pace based on the results of the first well. Production increased rapidly as a result of the deepening of exploration boreholes: by the end of 1941, the 22 wells already provided 138 thousand tons of crude oil and 39 million cubic meters of gas. In 1942, the amount of oil in Lovász exceeded that of the Budafapuszta field: 47 oil wells and two gas wells produced 340 thousand tons of oil and 105 million cubic meters of natural gas. By the end of 1943, the field had 74 oil wells and two gas wells, with a yield of 497,000 tons of crude oil and 151 million cubic meters of gas. In 1944, oil production decreased even with increased drilling activity: 493 thousand tons of oil were extracted from 89 oil wells. On the other hand, gas yield has increased, reaching two hundred million cubic meters per year."

"The units of the Soviet army pushed the German troops out of the area of the Lovász plant on April 4, 1945. After the restoration of the basic equipment, production could start again on 10 April."

"The production of the Lovász field also decreased: in 1945 it produced 405 thousand, in 1946 393 thousand, in 1947 340 thousand, and in 1948 only 285 thousand tons. The significant decrease in crude oil production was the consequence of a much higher than permissible predatory economy, in addition to the natural decline in yield. Increasing gas repression could have partially offset the rapid decline in stratum energy, but the necessary compressor capacity was not available to reinject the large amount of gas that came to the surface with crude oil through forced production."

"The daily gas production of the Lovász field in June 1945 was around six hundred and fifty thousand cubic meters, of which eighty thousand cubic meters of gasoline-rich wet gas and two hundred thousand cubic meters of dry gas remained unused. The idea of gas soot production for the utilization of unused gas released into the air was raised at MAORT as early as 1941, and it gained a new meaning after 1945, in the period of increasing gas production.

Although it has been formulated that gas soot production is the most inefficient way of utilizing natural gas, as it sells only two to three and a half percent of the coal in gas, its implementation – in addition to selling unused gas – would save the Hungarian economy from importing gas soot, which is essential for the rubber and paint industry."

"Another option for the sale of extracted but unused gas, which was considered important primarily by the state governing bodies, was its use for the gas supply of cities, especially Budapest. Due to its deteriorated financial situation, MAORT could not undertake the construction of a separate gas pipeline. The company's engineers solved the task in a novel way: Andor Czupor and Zoltán Gyulay worked out a method for transporting natural gas together with oil through an oil pipeline. Successful transport attempts were carried out at the end of October 1948 in Lovászi."

"In May 1945, MAORT experts began to work on a plan to extract edible salt from the salty aquifer water of the L-98 well. The salt distillation equipment was put into operation in May 1946, and in July and August, two thousand five hundred kilograms of salt were obtained per month. The plant operated until the end of April 1947."

"This phase of the history of the Lovász hydrocarbon field was not free of emergencies. There were three well eruptions. The first major eruption in the Transdanubian oil fields occurred in October 1944 at the L-94 well, which was being drilled, during rescue work. The erupting gas ignited, and the fire could only be extinguished by blasting at the cost of lengthy operations. The well collapsed later (in December), and gas eruption ceased. In June 1946, the L-110 well erupted. The erosion effect of the sandy gas flowing out of the well made it impossible to shut off the eruption barrier. The collapse of the hole stifled the eruption. The gas discharge caused by the "stray" gases from this eruption in February 1949 at the L-150 well. The erosion effect of sandy gas production cut off the wellhead assembly. Because of the amount of sand that was extracted, the eruption suffocated itself."

"This period of the life of the field, which was not without difficulties, was closed by the state administration of MAORT (24 September 1948) and then its nationalization (31 December 1949). This was directly preceded by the show trial, the so-called MAORT sabotage trial, which imposed extremely severe sentences on the leaders of MAORT (dr. Simon Papp, Béla Binder, Ábel Bódog), and symbolically put the entire professional staff of the industry on the bench of the accused. The harmful effects of this can still be felt today."

"With effect from 1 January 1962, the South Transdanubian Oil and Gas Production Company was established by merging the Lovász and Budafa Petroleum Production Companies, and on 1 January 1964, the Transdanubian Oil and Natural Gas Production Company was established by merging the Nagylengyel Petroleum and Natural Gas Production Company and the Transdanubian Oil and Natural Gas Production Company. On 1 January 1978, another reorganization took place, and the Oil and Natural Gas Mining Company was established with its headquarters in Nagykanizsa by merging the Transdanubian Oil and Natural Gas Production Company, the Transdanubian Research and Exploration Plant and the Nagyalföld Oil and Natural Gas Production Company. With the reorganization of the National Oil and Gas Trust, the oil mining plants in Zala became the plants of the Hungarian Oil and Gas Industry Co. (MOL Rt.), established in 1991.

At the time of the state management, oil was produced from 107 wells in the Lovász oil field. Of these, 65 wells operated with ascending production, 38 auxiliary gases, one deep pump, and three pistons. The average distance between the wells in the field was three hundred meters. The main characteristic of the years after the state took it into state management – despite the contrary opinion of experts – is that the principle of "more oil at all costs" has become decisive. In order to stop the decline in oil production, thickening drilling has begun, and the well distances have been halved. The disregard for sober technical considerations developed on the basis of natural laws later backfired."

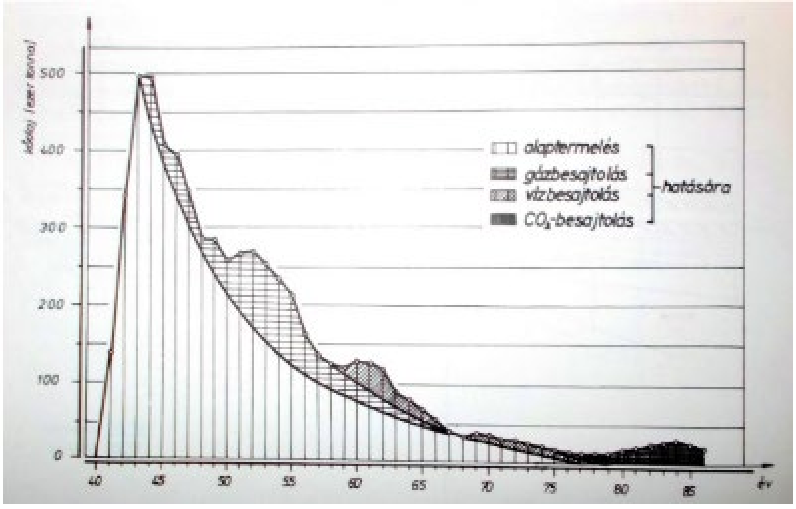
The application of oil-water extrusion cultivation began in 1953–1954. The largest amount of water injection occurred in the lower Rátka layer. The periphery water injection method was used until mid-1963, but based on its experience, territorial flooding experiments were started in 1966. Experiments with carbon dioxide injection in the laboratory began as early as 1953. The first small-scale experiments took place between 1962 and 1964 in the Lovász field, when the boilers of the gasoline plant pushed carbon dioxide and water obtained from natural gas into the layer together.

In the mid-1970s, two distribution centres were put into operation in the Lovász field for the purpose of carbon dioxide cultivation. The natural gas containing carbon dioxide necessary for cultivation was transported from the Budafa field to Lovászi on a high-pressure transmission line. The required amount of water was provided by the aquifer water produced and the wells of the Muraszemenye waterworks. Carbon dioxide cultivation was implemented in the Lovász series with a gradual territorial expansion, which provided the majority of the oil production of the field. In addition to the application of new, modern cultivation methods, Lovászi also played a significant role in the development of stratum management methods. The first successful trial of rock fracturing methods took place here in 1957. In the 1960s, complex chemical layer treatment was developed instead of the previous simple layer acidification to improve the permeability of rocks, and then applied to increase the yield of the wells of the Lovász field.

Until 1990, a total of 478 boreholes were deepened in the area of the Lovász field, of which on 31 December 1989 72 wells still produced hydrocarbons, 35 were carbon dioxide water injection and 45 wells performed observation functions."

"Three to five drilling rigs worked in Lovászi for several decades. In the history of the drilling of the field, the directed oblique exploration boreholes carried out since 1963 deserve attention, of which about thirty were deepened. The oblique boreholes became necessary due to the location of the already built housing estate and production facilities. In addition to drilling in the field at a depth of one thousand two hundred to six hundred meters, the drilling equipment also carried out a large amount of drilling research."

"In Lovászi, we managed to drill deeper than the four thousand meter and five-thousand-meter depth limits for the first time in Hungary. The L-I and L-II deep boreholes did not confirm the earlier hope of the geologists of MAORT that more significant hydrocarbon reserves can still be expected in this area at greater depths. The area of Lovászi was an open sea basin in the geological past, the clay layers deposited during the Miocene period are not suitable for storing stocks worth extracting."



21. Figure: The natural life cycle of the Lovászi field,
and the impact of different productivity-enhancing processes [15]

"Until the beginning of January 1990, 6,466 thousand tons of oil were extracted from the Lovász field. This is 30.3 percent of the initial geological oil reserve. Although a larger proportion of the oil reserves are still in the depths of the earth, significantly larger extraction with traditional technologies is no longer possible." During the extraction of this oil quota, approx. 24.2 million Nm^3[15] direct methane emissions had to be reckoned with. **In this project, gas extraction was only a by-product of oil extraction for a long time, a problem to be solved. For a long time, the extracted gas was only released into the open air, then a gas soot factory was built and soot was produced that could be used in rubber production. Later, natural gas was injected back into the wells along with carbon dioxide to increase oil production. Attempts were made to emulate the gas to transport oil and gas to the oil and transport it as wet oil through pipelines, finally separating the gas from the oil at the point of use.** *The example of the use of flares and ventilated gas soot inspired the (8.2that 53 "The complex retrofit monitoring and zero-methane catalytic flare, ventilation and leakage utilization system." RDI topic proposal.*

"A British exploration company found a significant amount of natural gas along the Slovenian-Hungarian border in the summer of 2011. The British Ascent Resources has found about 11.7 billion cubic meters of natural gas in the Petesháza (Petisovci)-Lovászi area along the Hungarian-Slovenian border, the weekly newsletter of the Slovenian government reported. According to Ascent, which specialises in oil and gas exploration and production, the amount of natural gas in the 200-square-kilometre exploration area was estimated based on the first three-dimensional models. The company believes that this could be the most economically exploitable natural gas field in mainland Europe. In February, further tests will be carried out in the area near Lendava, Slovenia, and gas production is scheduled to begin in mid-2012. The British company has a 75 percent stake in the project. The rest is the Lendava-based newspaper of the Prekmurje Hungarians, the *Néplap* – currently announced for sale. Ascent Resources' website states that the company has a 50 percent interest in the research project conducted in the Lovászi area of Zala County in Hungary, and through its subsidiary, PetroHungaria Kft., 48.8 percent in the production in the Nyírség-Penészlek area, but it also has partial exploration rights in the area south of Nagykanizsa, near Bajcsa. The company also has interests in Slovenia, Italy, Switzerland and the Netherlands." [16]

1.5.3. Üllés and Forráskút

These settlements are located in Csongrád-Csanád county and are also significant extraction sites. "Between Forráskút and Üllés, they have been searching for oil or natural gas for a month (2015-06-10), and soon they will reach the planned depth of 2950 meters. The purpose of drilling is to increase the amount of oil and gas extracted in Hungary and to increase domestic energy security. In the 60s, on the one hand, the technology was less developed, and on the other hand, the deeper layers were not even explored by oilers. But they knew that there were hydrocarbons at Forráskút. In 1963, for example, the Üllés 1 oil production well was opened nearby. In the vicinity of Forráskút, 11 wells have already been drilled, some of which were barren boreholes that were used as thermal wells by the locals. "We have been searching for oil and natural gas in the vicinity of Forráskút since 1975, and the works were completed around 1985. With the winning of the concession right, we were able to continue the mapping of the area and further drilling exploration: the Forráskút Dél 1 well is the first in line, and we will drill the second one next year. The 3D seismic measurement of the area was carried out last year: experts built a geological model from this and the existing information. Based on this, the point on the surface where the equipment could be installed was designated, then the licensing process, the preparation of the drilling point, the transport and construction of the drilling rig followed. This happened a month ago, when the drilling started, which will last a total of 65 days: we have just reached the halfway point," said Tamás Szabó, Mol's head of well management.

22. Figure: Natural gas exploration at Üllés-Forráskút in 2015 [17]

The drilling rig is located between Forráskút and Üllés, only a few 100 meters from the road connecting the two settlements, right in the middle of the cultivated hectares. The oilers used an area of 100 by 120 meters, on which the 250-ton equipment is "working". 5 cubic meters of diesel are used per day to produce the electrical energy needed for the power plants locally." [17]

1.5.4. Endrőd

23. Figure: The gas extraction site in Endrőd [18]

"**MOL has taken another strategic step to strengthen Hungary's energy security: it has acquired O&GD's gas fields and related infrastructure located in the Endrőd area, covering an area of approximately 1000 km2.**

There are currently 29 wells in the area trained for hydrocarbon production, the current daily production is about 1000 barrels equivalent, and the mining plots offer additional exploration opportunities."

"This agreement fits perfectly into MOL's long-term strategy, one of the goals of which is to maximize hydrocarbon production and increase energy security.

Thanks to its inherent gas extraction potential, this field can play a key role in the Hungarian energy supply not only in the short term, but also in the coming years, and the related infrastructure has significant synergy potential with other assets in the MOL region," said Zsombor Marton, Managing Director of MOL Group's Exploration and Production.

"MOL plans to invest approximately one hundred and fifty billion forints in domestic oil and natural gas production over the next three years, part of which is directed to the development of natural gas projects.

The purchase of the Endrőd gas field is another important milestone on this path, which will help strengthen Hungary's energy independence in the long term," emphasized Dr. György Bacsa, Managing Director of MOL Hungary.

The acquisition of O&GD's gas fields in Endrőd contributes to MOL's objective of providing the country with as many hydrocarbons as possible from domestic sources. MOL is the largest hydrocarbon producer in Hungary, producing at almost 1300 oil and natural gas wells.

In 2024, MOL provided 47% of crude oil (almost 600 thousand tonnes) and nearly 80% of natural gas (almost 1.5 billion m3) of domestic production. MOL Group also has the most significant oil and gas production portfolio in Hungary, currently accounting for nearly 40% of total production.

The cooperation between MOL and O&GD goes back several years. In the summer of 2023, MOL acquired a 49% stake in O&GD's three exploration concessions, and in 2024, as a result of their joint work, they discovered a new, previously unknown crude oil deposit near Tura." [18]

1.5.5. Pusztaföldvár

It is located in Csongrád-Csanád County and is considered one of the oldest natural gas deposits in Hungary.

1.5.6. The surroundings of Szank and Kiskunhalas

There are several smaller and larger natural gas fields in Bács-Kiskun County, which play a significant role in the domestic supply. Extraction in the vicinity of Szank started as early as the 1960s.

1.5.7. Hajdúszoboszló

It is one of the most important natural gas deposits in Hajdú-Bihar County. Extraction began in the 1950s and it became the energy center of the region. There are significant natural gas reserves in the area of Hajdúszoboszló, especially in the form of the so-called "cushion gas". In 2022, the MVM Group announced that the extraction of cushion gas could begin in Hajdúszoboszló, which means the gas reserve in underground gas storage facilities that plays a pressure-balancing role. Hajdúszoboszló has access to cheaper natural gas at a net price of HUF 935/cubic meter, which can mean significant savings for the population and the municipality. The 2022 production of cushion gas is part of a broader effort for Hungary to reduce its dependence on imports and increase its energy independence. [19]

1.5.8. Minor extraction sites

In addition to the above-mentioned larger fields, a number of smaller deposits also contribute to domestic natural gas extraction, such as Kardoskút, Szeghalom, and some smaller fields in Transdanubia. Together, these smaller locations provide a significant amount of domestic production.

1.6. Extraction, Transfer, Receipt and Storage

The natural gas extracted is largely transported to consumers through local pipelines, and some is stored in underground gas storage facilities to meet the growing demand during the winter period. There are several large natural gas storage facilities in Hungary, such as near Zsana, Kardoskút, Hajdúszoboszló and Pusztaederics.

24. Figure: Natural gas inflows and outflows on 05.08.2025 [3]

25. Figure: Domestic natural gas transfer, takeover and storage stocks as of 05.08.2025 [3]

They also transport a significant amount of natural gas through Hungary. Not only do we have to examine the methane emissions of locally extracted, imported natural gas, but we also have to take into account the emissions of transit (5.8 billion Nm^3/year2024) natural gas transport and storage.

The proportions of which are comparable to domestic consumption (8.5 billion Nm^3/year in 2024). Methane emissions (approx. 3% of domestic production) of natural gas transmission and storage (approx. 3%) in 2024 and transit (13.9 billion Nm^3/year $_{\text{in 2024}}$) are estimated to be 411 million m^3/year.

2. Methane emissions related to natural gas transmission

26. Figure: Natural gas distribution system [11]

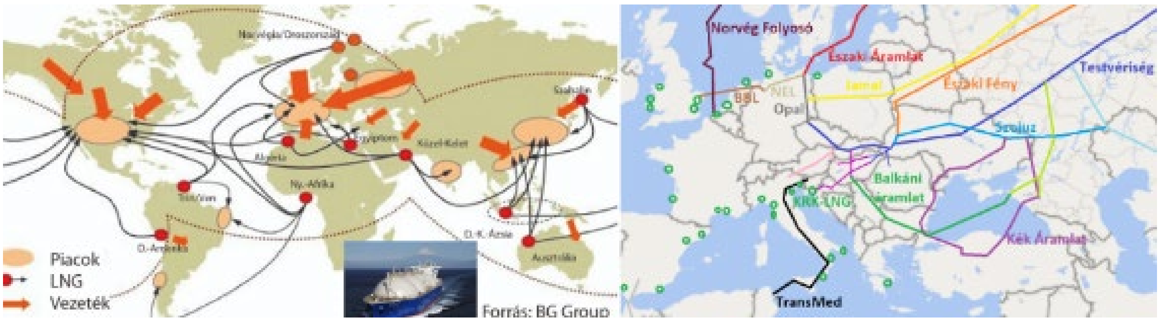
1. GAS FIELD PRODUCTION; **2.** GAS PREPARATION PLANT - Processing, cleaning; **3.** Power cord; **4.** Compressor station; **5.** Storage; **6.** Distribution license holder or gas distribution company; **7.** Distribution lines to CUSTOMERS; **8.** Connecting wires; **9.** Gas consumption meter; **10.** Residential consumer / combustion appliance) [11]

At the deposits, natural gas is extracted from gas wells, from where it is transported to one of the gas collection stations, and then to the preparatory plant, where gas preparation takes place.

At production sites, the well pressure is usually sufficient to feed the gas into the transmission line. By the way, pressure booster compressor stations operate on the high-pressure natural gas transmission system every 200 kilometres or so, ensuring adequate further transport.

The prepared natural gas reaches the gas transmission stations in this pipeline system (breaking its path with dismemberment stations), through which it is forwarded either to a related gas distribution company or to a large consumer (e.g. power plants, factories).

At the gas transfer station (distribution entry point), filtration, heating, pressure reduction and measurement are carried out. They sell the natural gas flowing in the transmission line. This is how it is made available to residential and industrial consumers.



27. Figure: The journey of gas in the world, to Europe, to Hungary [11]

In The supply chain of natural gas, Methane leaks can occur at several points during the extraction, processing, transport and distribution of natural gas. The main stages of the supply chain are:

- Extraction (wells, drilling equipment)
- Processing (cleaning, drying, compression)
- Transport (high-pressure lines, compressor stations)
- Distribution (local lines, delivery to end users)

Methane emissions can occur at each stage, but the middle part of the supply chain – high-pressure lines and compressor stations – is particularly critical in this regard.

Main sources of methane emissions during transport

- ***Compressor stations***: These facilities maintain the flow of natural gas in the pipelines. Significant amounts of methane can be released into the atmosphere from compressor seals and valves, as well as during maintenance and cleaning operations.

- ***Pipe leaks:*** Pipe joints, damage, or old materials are often leaked in small or large sizes.

- ***Fracking and ventilation:*** In the event of certain maintenance work or malfunctions, excess natural gas (i.e. methane) is emitted by flaring or ventilation.

2.1. Natural gas pipelines in Hungary

Transmission pipeline together with the pipeline accessories through which natural gas is transmitted, the starting point of which is the state border of Hungary, the entry points of production, the entry and exit point of the natural gas storage facility, and its end point is the state border of Hungary, the exit points of the gas transmission stations – or, according to the permit, the property boundary of the user or the entry and exit point of the natural gas storage facility.

A distribution line usually runs from the exit point of the gas transfer stations to the plot boundary of the place of use. Within the plot boundary**, together with the accessories of the private pipeline**, through which the natural gas reaches the user equipment. Every pipe connection, valve and meter is a new leak point. In Hungary, FGSZ Ltd. and MGT Ltd. hold transmission system operator licenses. The former company owns and operates the nearly 5'800 km long domestic high-pressure natural gas transmission pipeline system. The FGSZ system networks our country so that pipeline natural gas can reach settlements anywhere in Hungary, thus ensuring the benefits and convenience of gas. The typical diameter of the gas pipeline system is 100-1400 mm, its operating pressure is 40-75 bar, and its average age is nearly 30 years. In order to ensure maximum security of supply and the rapid flow of information, there is also a 7030-kilometre-long telecommunication system running mainly next to the gas pipelines, which ensures the remote monitoring and control of the transmission system, as well as gas market applications related to the licensed activity.

28. Figure: High-pressure natural gas transmission pipeline system in Hungary [11]

FGSZ ensures the receipt, quantitative and qualitative measurement of natural gas from domestic production, imports and underground storage facilities at 20 domestic and 4 import entry points. In Báta, Beregdaróc, Hajdúszoboszló, Mosonmagyaróvár, Nemesbikk and Városföld, a compressor station is responsible for boosting the pressure and supplying consumers with natural gas in the right quantity and pressure.

The appropriately smelled natural gas reaches the connecting system operators and direct industrial consumers through nearly 400 outlet points, so that the quantity and quality of natural gas are measured at each entry and outlet point.

Every year, FGSZ prepares a 10-year development plan, which includes all the developments that include the investments necessary for the development of the domestic natural gas system from the point of view of security of supply and regional market construction. The connection of domestic gas transmission pipelines with similar systems in neighboring countries will make it possible to increase the energy security of the Central European region and diversify natural gas supply routes.

The latest result of these efforts is the construction of the Hungarian-Slovak high-pressure gas pipeline owned and operated by Magyar Gáz Tranzit Zrt. (MGT Zrt.). This pipeline is an important element of the North-South gas corridor, which will provide a connection between the natural gas pipeline systems from Croatia to Poland.

The gas corridor to be built will also make new gas sources available (planned LNG and shale gas in Poland). The Hungarian-Slovak interconnector may have a decisive impact on the consumer gas market environment from the point of view of security of supply and the promotion of gas price competition by its mere availability; the pipeline will be able to provide Hungary with a competitive source of gas. Knowing the domestic gas demands, the amount needed for the country's gas supply can be imported together through the Hungarian-Austrian Gaspipeline (HAG), which allows transport from the West, and the Hungarian-Slovakian interconnector, even if our imports from Ukraine are cut off.

The Hungarian section of the approximately 111 km long, two-way pipeline with a DN diameter of 800 mm and a pressure of 75 bar is 92 km long, with two Hungarian terminas at Vecsés and Balassagyarmat. Its Slovakian section is 19 km long and its end point is at Felsőzellő. The planned capacity of the new natural gas pipeline is 500,000 m^3/h in the Slovak Hungarian direction, i.e. approximately 4 billion m^3/year, and 200,000 m^3/h in the Hungarian Slovak direction, which means a volume of nearly 1.6 billion m^3/year. The new transmission line is operated by MAGYAR GÁZ TRANZIT Zrt." [11]

2.2. Natural gas pressure booster stations

A natural gas pressure boosting station (also known as a compressor station) is a facility that increases the pressure of natural gas flowing through a pipeline so that it can travel long distances and reach consumers at the right pressure. The stations are usually located at strategic points in the gas pipeline network, often hundreds of kilometres apart. Natural gas travels from the point of extraction to the point of consumption through long pipelines. During the journey, the pressure naturally decreases, so it is necessary to periodically increase the pressure. At the heart of the stations are compressors, which are powered by mechanical or gas turbines and compress natural gas. Modern stations are highly automated, continuously monitoring pressure, temperature and flow rate to keep the system safe and efficient. In Hungary, gas **turbines** are mainly used to drive compression machines **at the compressor stations of the natural gas transmission system, while gas engines** are more likely to operate in smaller power plants and industrial facilities.

FGSZ Ltd. operates the Hungarian high-pressure natural gas transmission system. At the compressor stations (e.g. Hajdúszoboszló, Mosonmagyaróvár, Gellénháza, Városföld, Nemesbikk), the compressors are driven by high-performance gas turbines. These turbines typically have a capacity of 10 to 25 MW and are necessary to ensure the continuous supply of gas. According to the official data of FGSZ, there are more than 20 compressor stations in Hungary, and each of them has several gas turbines, so the number is a few dozen. These stations also have gas engines to maintain part-load operation. But the almost 2000 gas engines found in Hungary are mainly used in smaller power plants, district heating and biogas plants. Their output is usually between 0.5 and 5 MW.

Station	Location	Estimated number of gas turbines	Comment
Hajdúszoboszló	Eastern Hungary	~8	One of the largest capacity stations
Mosonmagyaróvár	Western Hungary	~6	Important international transit point (to Austria)
Gellénháza	Western Transdanubia	~5	Regional distribution role
Városföld	Central Hungary	~10	Strategic center, delivers in several directions

Station	Location	Estimated number of gas turbines	Comment
Nemesbikk	Northeast Hungary	~7	Key in transit to Ukraine

2. Table: Estimated number of pressure boosting gas turbines [21]

The estimated number of pressure boosting gas turbines is 36 pcs, their total estimated capacity is 1260 MW, which after 7200 expected operating hours is 9'072' 000 MWh, i.e. 32'659'200 MJ, which requires 2'825'190 Nm^3 of natural gas assuming a system efficiency of 34%. The annual need to maintain pressure boosting means a methane load of 3% (assuming leakage, ventilation and other specific methane emissions) of 84'755 Nm^3.

29. Figure: The first step of the pressure boosting process is the filtration of the natural gas arriving through the transmission line [3]

Filter blocks filter out liquefied and solid contaminants from natural gas to protect high-speed compressors from damage.

30. Figure: Natural gas is transported at high pressure (40-75 bar) [3]

The pressurization of the filtered natural gas is carried out by centrifugal compressors driven by gas turbines.

2.2.1. Function and principle of operation

- **Pressure Build-up:** Natural gas travels from the point of extraction to the point of consumption through long pipelines. During the journey, the pressure naturally decreases, so it is necessary to periodically increase the pressure.
- **Compressors:** At the heart of the stations are compressors, which are mechanically or turbine-powered and compress natural gas.
- **Automation and safety:** Modern stations are highly automated, constantly monitoring pressure, temperature, and flow rate to keep the system safe and efficient.

2.2.2. Types of booster stations

1. **Main Pipeline Compressor Stations:** These are located along pipelines and are designed to ensure the transport of natural gas over long distances.
2. **Distribution stations:** These are located closer to consumers and reduce or regulate the pressure of the gas to the level of end use.

2.2.3. Technical features

- **Compressor types:** The most commonly used are centrifugal and piston compressors.

31. Figure: 6-stage centrifugal compressor [3]

The rotating blades of the gas compressor accelerate the transported gas, the flow rate of which in some cases approaches the speed of sound.

Therefore, it is important to filter the natural gas before starting the pressurization, as liquid impurities would cause blade damage due to hydraulic impact, and solid particles would grind and wear out the parts.

In the diffuser following the rotating blades, the gas is braked, and a significant part of the kinetic energy is converted into compressive energy.

This is how the compressor creates the required gas pressure in the transmission line.

- **Energy source:** Can be electric, gas turbine, diesel or gas powered by a diesel or gas engine.

32. Figure: Gas turbine [3]

The gas turbine's multi-stage axial compressor draws in ambient air through an air filter and then compresses it. The air with a pressure of 10-16 bar mixes with natural gas in the fuel gas nozzles. The air-natural gas mixture burns in the combustion chamber, where a temperature of approximately 1’500°C is created.

The hot combustion product passes through the turbine stages at high speed, and then the kinetic energy generated by the thermal energy during expansion sets the gas compressor in rotation through the gas turbine shaft. Gas turbines drive centrifugal compressors because these types of devices are best suited for transporting large quantities of natural gas (300’000–1’000’000 Nm^3 per hour).

33. Figure: The compressor and the gas turbine are built into a common cabin, container [3]

34. Figure: Outdoor compressor unit manufactured by Solar Turbines Inc. [3]

- **Safety systems:** Fire and gas detectors, overpressure protection, automatic shutdown functions.

In the smaller power categories of 0.5-5 MW, piston gas engines are mostly used, and above that, in the power category of up to 30-40 MW, gas turbines are more commonly used. At the Hungarian compressor stations, more than 175 coherently assembled compressor groups of different capacities increase the pressure of the pipeline system, providing the current needs. Gas engines provide decentralized energy production, often directly at the point of consumption.

Biogas plants contribute to increasing the share of renewable energy and reduce the environmental impact of waste. Gas engines can be flexibly started and stopped, making them well suited to the regulatory needs of the electricity system.

Facility Type	Estimated number of units	Power Range	Comment
Biogas plants	~38 plants	0.5–3 MW/gas engine	Waste, sewage sludge, animal husbandry by-products
District heating providers	~50–60 locations	1–5 MW/gas engine	Urban heat supply, decentralized power generation
Industrial sites	~100+ gas engines	0.5 to 5 MW	Own energy supply, cogeneration
Altogether	~200–300 gas engines	0.5 to 5 MW	At the national level

3. Table: Estimated number of gas engines in operation in Hungary [3]

There are significantly more gas engines in Hungary out of service. Which have been widely invested in cogeneration (electricity generation-heating) operation. In some places, trigeneration (electricity generating – heating and cooling) design has also been invested. In the case of condensation design, these variants still mean a modern, high, almost complete heat energy utilization. Until 2008, their distribution increased rapidly. More than 2000 were relocated, when the gas price support system was abolished and the price of natural gas also increased several times. The production capacity of these decentralized gas engines in the case of a renewable biomass gasification, collection and storage system would mean an excellent standby hidden capacity. Especially in the decentralized regulation of the weather uncertainties of the significant solar panel capacity installed in recent years.

2.2.4. Their significance in the Hungarian gas network

Due to its geographical location, Hungary is an important transit country for the transport of natural gas. Domestic booster stations play a key role in meeting both international and domestic consumer demands. Natural gas pressure boosting stations are indispensable in modern energy infrastructure. These stations ensure that natural gas is transported reliably and safely from the point of extraction to consumers, thus contributing to the smooth running of everyday life, the operation of industry and the country's energy supply. The collection of hitherto unused emissions from ventilation and leakage and the technical implementation of their return to the turbines by means of intake air (EGR) could be an economically profitable environmental investment in a few years (8.1 that 52. page).

2.2.5. Szolnok

35. Figure: Natural gas pressure boosting site, Szolnok [3]

2.2.6. Nyárlőrinc

36. Figure: Natural gas pressure boosting site, Nyárlőrinc [3]

3. Methane emissions from natural gas storage

37. Figure: Location of natural gas storage facilities in Hungary [3]

"Four underground gas storage facilities are currently in operation: Pusztaederics, Kardoskút, Hajdúszoboszló and Zsana – with a total of 4.43 billion Nm^3 of mobile gas storage facilities plus 420 million m3 of additional capacity. In 2024, the volume flow of stored gas was 6.4 billion Nm^3 of natural gas. They can store and receive from storage capacities several times during the year. In Hungary, gas storage facilities have a porous geological structure. In most cases, the rock is sandstone (Hajdúszoboszló, Pusztaederics, Kardoskút), with one exception (Zsana), where it is limestone. These geological formations, from which the extraction of natural gas has been partially or completely completed and it has been proven that they are suitable for storing natural gas, have been converted into underground gas storage facilities. The restructuring extensive:

- the conversion of wells originally used for gas extraction, the drilling of new ones if necessary;
- the construction of a natural gas collection and distribution system;
- the installation of related injection and gas preparation equipment;
- and the construction of appropriate transmission line connections.

The first underground gas storage facility in Hungary was built near Őrszentmiklós to store natural gas produced in this region. From 1960 onwards, the natural gas stored here also contributed to meeting the peak demand in Budapest during the winter periods. However, the continuous increase in the demand for natural gas has made it necessary to establish additional underground gas storage facilities. The program started in 1978 with the transformation of partially cultivated natural gas fields in the area of Kardoskút, and continued the following year with the commissioning of two more facilities in Hajdúszoboszló and Pusztaederics.

Storage cycles:

Start of the injection period: 1 April
End of the injection period: 30 September
Start of withdrawal period: 1 October
Withdrawal period ends: 31 March

Natural gas storage facilities

For natural gas storage purposes, only the natural gas storage layer can be considered,

- which has been proven to be closed for future storage operation,

- where the storage rock itself has the necessary storage properties and is also sufficiently stable,
- where natural gas can be injected and stored relatively easily and economically and fully recovered from the storage layer.

Only a fraction of a hundred cultivated fields meet these expectations. Of course, in addition to technical considerations, economic calculations also play a role in the selection of the storage location. For example, it is a basic expectation that natural gas can be injected with a relatively low pressure of 60-80 bar or a maximum of 210 bar. This is fulfilled if the site is no deeper than 2000-2500 meters and its storage rock has good permeability.

3.1. Pusztaederics

The Pusztaederics gas storage facility operates in lower Pannonian sandstone (upper and lower nova deposits, Szolnok Sandstone Formation). The storage facility was created through the utilization of the former natural gas field produced in Hahót-Ederics. The idea of creating a storage facility was raised in the seventies. In the period between 1972 and 1979, 5 former natural gas extraction wells were already used for gas storage, making the Pusztaederics facility the first natural gas storage facility in Hungary. By 1979, 7 more wells were completed, when the facility was officially classified as a natural gas storage facility. At that time, the total of 12 stations had a mobile gas capacity of 100 million cubic meters. In 1988, this capacity was increased by 100 million cubic meters, and in 1991, new wells were established in the course of further developments. The current nominal mobile gas capacity is 340 million cubic meters. The daily withdrawal capacity is 2.9 million m^3, while the injection capacity is 2.9 million m^3 per day. The amount of cushion gas that ensures the smooth operation of the storage facility is 266 million m^3. The project to extend the life of the storage facility has recently been completed, which is intended to ensure the uninterrupted operation of the storage facility in the future.

The Pusztederics facility is the only natural gas storage facility in Transdanubia, thus playing an important role in maintaining the hydraulic balance of the high-pressure pipeline system in the western part of the country.

Storage capacity **Pusztaederics**	
Mobile gas capacity:	340 MNm^3
Withdrawal capacity:	2.9 MNm^3/day
Injection capacity:	2.9 MNm^3/day

4. Table: Pusztaederics storage capacity [3]

3.2. Hajdúszoboszló

Hajdúszoboszló was once the most important natural gas deposit in Hungary. The era of natural gas began in Hungary with the exploitation of deposits discovered during the fifties. During the peak period of natural gas production, from the end of the sixties, 1.8 billion m^3 of natural gas was brought to the surface annually from the Hajdúszoboszló field. The construction of the storage facility began in 1977, and in 1981 the storage facility's 35 wells equipped with special sand filters were capable of accommodating 400 million m^3 of mobile gas.

In the course of further developments, the mobile gas capacity of the storage facility has reached 1640 million cubic meters. From the nineties, reconstruction works began that ensure the existing capacities of the repository for the long term.

The storage facility, which currently has a nominal mobile gas capacity of 1,640 million, has a daily withdrawal capacity of 16 million Nm^3, while the injection capacity is 10.3 million Nm^3 per day.

Storage capacity Hajdúszoboszló	
Mobile gas capacity:	**1640** M Nm^3
Withdrawal capacity:	**16** MNm^3/day
Injection capacity:	**10.3** MNm^3/day

5. Table: Storage capacity of Hajdúszoboszló [3]

3.3. Zsana

In the area of the village of Zsana, the search for hydrocarbons began in 1978. In the ten years between 1982 and 1992, about 4 billion m^3 of gas was extracted from the Zsana gas plants, and in 1992 the construction of the Zsana gas storage facility began. The initial capacity of the storage facility was 600 million cubic meters, and the first withdrawal took place in November 1996. At that time, the daily withdrawal capacity of the storage facility was around 8 million cubic meters. Due to its geological features (limestone storage), the Zsana storage facility is the most flexible natural gas storage facility in Hungary. At a depth of 1695-1780 m below sea level, 4 layers are involved in the storage of natural gas.

As a result of the multi-stage expansion, the storage capacity increased to 1570 million m^3 by 2008, with a peak capacity of 24 million m^3/day for production and 10.2 million m^3/day for injection. In the summer of 2008, the further expansion of the storage facility began within the framework of an investment worth a total of HUF 32 billion. Thanks to the expansion, which was completed by the autumn of 2009, the storage capacity increased by 600 million cubic meters, bringing the total to nearly 2.2 billion cubic meters, and the withdrawal capacity increased to 28 million cubic meters per day. The injection capacity has also significantly increased to 17 million m^3/day thanks to the new turbo compressors.

Storage capacity, **Zsana**	
Mobile gas capacity:	**2170** MNm^3
Withdrawal capacity:	**28** MNm^3/day
Injection capacity:	**17** MNm^3/day

6. Table: Zsana's storage capacity [3]

3.4. Kardoskút

In 1960, a field containing a little more than 1 billion cubic meters of extractable natural gas was found in the vicinity of Kardoskút and Pusztaszőlős. Extraction began in 1966. After the plant was emptied, its utilization for natural gas storage purposes began in 1978, with only 7 wells at that time. Between 1980 and 1984, the surface facilities and injection capacity were expanded, which involved the drilling of several new wells. The average depth of the sandstone plant suitable for storing natural gas is 1000-1100 m. The storage facility in Kardoskút is currently operating with 21 production wells and 8 observation wells. Its current mobile gas capacity is 280 million cubic meters, and its withdrawal capacity is 2.9 million cubic meters per day.

Storage capacity, **Kardoskút**	
Mobile gas capacity:	280 MNm^3
Withdrawal capacity:	2.9 MNm^3/day
Injection capacity:	1.6 MNm^3/day

7. Table: Natural gas storage capacity of Kardoskút [3]

Hungary's total natural gas storage capacity is shown in Table 8.

Natural gas storage capacity in Hungary:

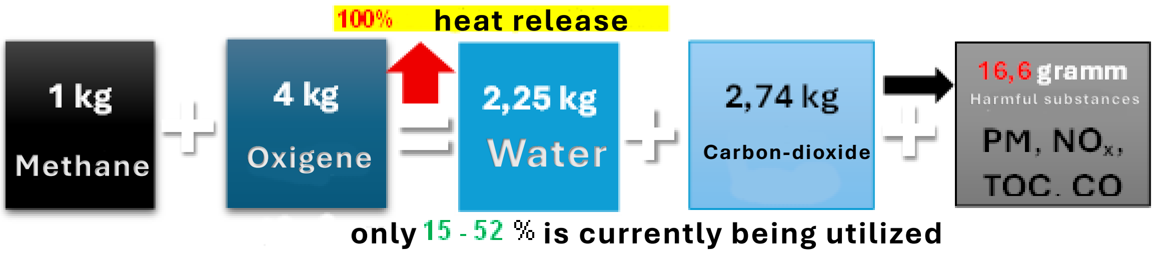
Storage capacity altogether	
Mobile gas capacity:	4430 MNm^3
Withdrawal capacity:	49.8 MNm^3/day
Injection capacity:	31.8 MNm^3/day

8. Table: Total domestic natural gas storage capacity [3]

The annual methane emissions of storage capacity must be taken into account with both injection and withdrawal operations, and accordingly the estimated amount is up to 216 million Nm^3.

4. Direct and indirect impact of methane emissions from natural gas processing on the climate

During the processing of natural gas, a significant amount (up to 3-4%) of methane can be released. It is mainly generated during various technological processes from leaks and during



38. figure: *CH4 during flame oxidation **1 kg** methane combustion in total **2.74 kg** carbonic acid gas **2.25 kg** water vapor and about **16.6 grams** harmful substances (PM, NOx, TOC, CO) are produced. If the natural gas also has hydrogen sulfide content, sulfur-oxides can also be formed from it during combustion [4]*

equipment maintenance. After the combustion of the methane used to produce the processing energy itself, direct (CO2) and indirect (PM, NOx, CO, TOC) gases are released that cause atmospheric warming and are also harmful to health. The combustion of methane in thermal power engines (gas boilers, piston internal combustion gas-powered two- and four-stroke engines, gas turbines) occur directly, and in diesel and gasoline-powered two- and four-stroke engines) most often takes place as flame-burning type oxidation. Ideally (Annex 1.sz) **1 kg** during the combustion of methane **2.74 kg** carbon dioxide and **2.25 kg** steam[9] and **49-50 MJ** heat[10] released.

The In reality, when natural gas is burned, the combustion is not perfect, and its composition and temperature are inhomogeneous. Thermal power engines used for the transport and use of natural gas, a significant number of harmful substances are also generated. During combustion, the flame front flows out of the combustion chamber and expands. If the temperature of the flame front drops below the ignition temperature and/or ignition concentration, the oxidation process is interrupted. Unburned hydrocarbon derivatives remain in the flue gas.

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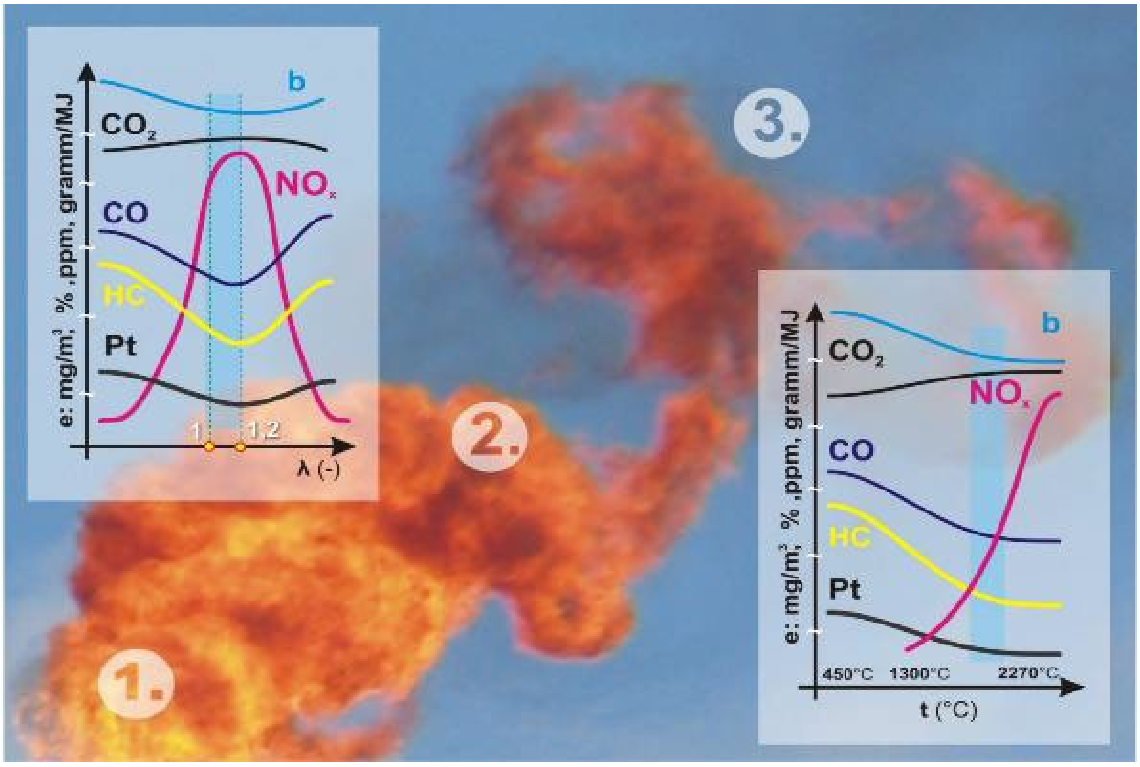
[9] *Water vapor has strong light absorption bands, especially: 0.94 µm and 1.13 µm – near-infrared, 1.38 µm and 1.9 µm – near-IR, strong bands of 2.7 µm and 6.3 µm – mid-infrared, very strong absorption. These bands are responsible for the greenhouse effect of water vapor because the above ranges of light reaching the Earth's surface are absorbed by the radiated heat.*

[10] *The heat losses of heat engines (Total amount of heat released – heat used in heat engines) heat the atmosphere directly.*



39. Figure: Harmful substances in the flue gas of the flame combustion of heat engines, depending on the temperature and excess air.
***(1.)** flame core, **(2.)** expanding flame plasma, **(3.)** Volume immediately after the flame peak [4]*

PM: The excess air in the vicinity of the flame core is so low (the ratio of fuel to air needed for its combustion) that even large amounts of soot particles[11] can be formed. The emitted soot – its mass flow – has the strongest specific effect on the climate, because not only the specific light absorber characteristic is high, but its indirect effect is outstandingly strong. It rises up to the stratosphere and sails primarily towards the Arctic, but to a lesser extent also towards the Antarctic. Settling there, it increases the light-absorbing capacity of snow and ice as a gray veil, optically catalyzing the melting of the ice sheet.

NO_x: With NO_x, several nitrous compound groups are denoted. It has a direct cooling effect on the climate, but the density of NO_1 is close to that of the air, so it can rise to the stratosphere, where it drastically destroys the ozone layer, oxidizing it to nitrogen dioxide. NO_2 is heavier than air. Near the earth's surface, photocatalytic decay produces NO_1 and O_3. The heat absorption capacity of ozone is significantly higher than that of carbon dioxide. A gas with a strong glass effect. Damage to the UV shield of the ozone shield also has an increased greenhouse effect, because more UV light can reach the earth's surface. The NO_x cycle deteriorates the atmosphere until it is washed away by rain. These gases cause acid rain, which damages forests, soils and waters, and reduces the carbon sequestration capacity of ecosystems. They are also very harmful to human health and the environment, thus reducing the body's resistance to the effects of climate change. N_2O (nitrous oxide) is not produced during the operation of thermal engines, it can be produced in large quantities during the degradation of biomass and the decomposition of fertilizer residues. In thermal power engines, N_2O burns without residue. It is rather used to enhance performance (nitro) in competitive sports. In thermal engines, the temperature of the flue gas can rise above 1000°C at the end of the flame peak, but a temperature focus of up to 2700°C can form.

[11] *Particulate Matter, or PM for short) is an umbrella term for airborne particulate matter. These are microscopic solid or liquid particles that come from various sources and have a serious impact on health and the environment. In the production of gas soot, excess air is deliberately degraded and this can be used to produce large quantities of activated carbon raw material, which is important for industry and economy.*

The excess air in these places is high. The air – its nitrogen content below 1000°C is intensely oxidized in the above temperature range. The climate impact of 1 gram of NO_x is equivalent to 445 grams of CO_2, which clearly shows that reducing nitrogen oxide emissions is also key to climate protection. [5]

TOC:[12] The sum of the hydrocarbon residues that have been imperfectly burned in the combustion chamber of a thermal engine. Up to hundreds of hydrocarbons. In the past, HC and E. HyCx. Instruments for measuring flares, gas engines and gas turbines detect and measure the methane equivalent. In the IPCC EU ETS labeling system, NMVOCs (non-methane, (all other) volatile organic compounds) are treated independently of methane. In the present model, the methane and methane equivalent emissions in the flue gases of thermal power plants are summed up, and their direct and indirect weather impact is simulated. Assuming that the above thermal power engines meet the relevant Hungarian EU compliant emission emissions. The simulation model is based on the limit value expressed in TOC, supported by measurements, the mass flow of which can be calculated from the actual natural gas consumption of the thermal power plant. [21]

CO: Hydrocarbons that have not yet been burned in the flue gas can retain significant amounts of carbon monoxide. Its effect on climate balance is not as great as that of the harmful emissions already presented above, but due to its effect on the human body, its effective elimination is very important.

SO_2: Sulphur oxides, especially sulphur dioxide (SO_2), have a significant impact on the climate, although they do not act as greenhouse gases. SO_2 reacts with water vapor in the atmosphere to form sulfurous acid (H_2SO_3) and then sulfuric acid (H_2SO_4), resulting in sulfate aerosols. These aerosols reflect solar radiation, thus having a cooling effect on the Earth. They promote cloud formation. Sulfate aerosols cause acid precipitation, which damages ecosystems, especially forests and soils, which reduces their ability to sequester carbon. Each gram of soot particle emitted from heat engines operating in accordance with current regulations corresponds to 1445 grams of CO2 emissions in terms of climate warming effect; this ratio is 445 grams for NOx, 84 grams for TOC for the first 20 years and 25 grams for 100 years, and 2 grams for CO. In processing plants such as Százhalombatta, Tiszaújváros or Kazincbarcika, the level of methane emissions depends to a large extent on the state of the art of technology, the measures taken to prevent leaks, and the quality of operation and maintenance. When determining the annual methane emissions, the emissions generated during injection and withdrawal operations must also be taken into account, as they are directly related to the processing process. It is estimated that the total methane emissions of domestic natural gas processing capacity could be up to 216 million Nm^3 per year, a significant part of which is released into the atmosphere during processing operations and storage.

4.1. Százhalombatta

Százhalombatta is home to one of Hungary's largest natural gas processing and oil refining centres. The technologies used are extremely energy-intensive, so a thermal power plant was built to utilize the residues of petroleum refining, in which heat and electricity are produced. Most of the electricity and heat produced is also used during operation.

The city is heated with the safety reserve of the generated standby energy and fed into the power grid. As stated above, the methane equivalent of TOC (unburned hydrocarbon derivatives) generated in technologies during energy supply is more significant than the methane directly emitted during leaks and ventilation.

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[12] The TOC label has several environmental meanings: it can be an environmental and water quality parameter that shows how much organic carbon is present in a given sample. In the case of the present simulation model, it does not refer to the characterization of water quality, but to the methane equivalent of all hydrocarbons not burned in thermal power plants.

40. Figure: Danube Crude Oil Refinery [12]

During the processing of natural gas, complex and modern technological operations are used, the aim of which is to purify the raw natural gas, separate its components, and optimize the quality of the final products.

The first step of the technological process is the removal of contaminants – sulfur compounds, water vapor, solid particles – which is carried out by various filtration, absorption and chemical processes.

After purification, the natural gas is fractionated, during which the various hydrocarbon components (such as ethane, propane or butane) are separated using modern cryogenic distillation and other separation technologies.

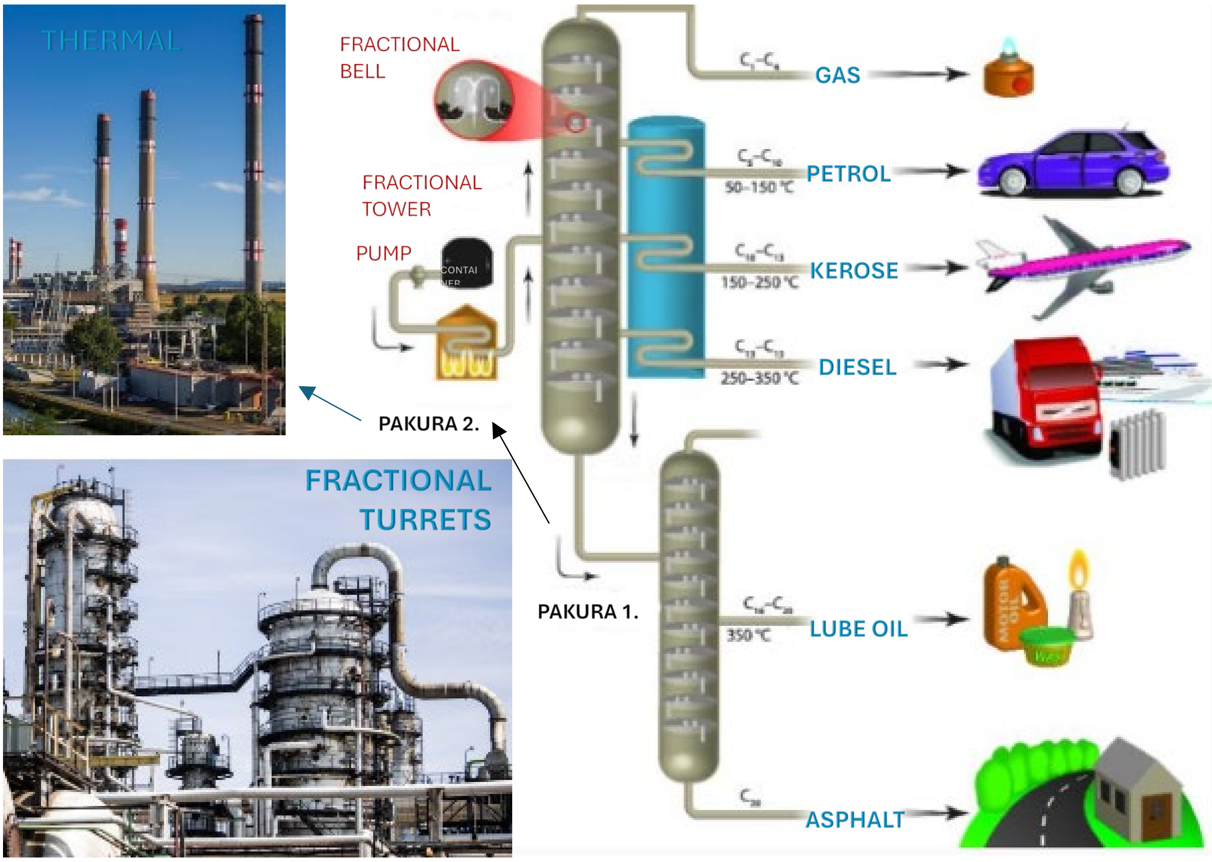
An important part of it is drying, during which the moisture present in the natural gas is extracted, as well as deodorization (removal of aromatic hydrocarbons and hydrogen sulfides), which is essential for safe consumer use.

The Danube Crude Oil Refinery in Százhalombatta is also Hungary's largest crude oil processing center, which plays a decisive role in the domestic fuel supply.

A significant proportion of the petrol, diesel and kerosene sold in Hungary is produced here, estimated to be up to 60-70%. Methane and other gaseous hydrocarbons with methane equivalent are also produced during the processing of crude oil.

Crude oil goes through a series of chemical operations to remove contaminants and optimize the quality of the final products.

As a first step, filtration, absorption and special chemical processes are used, during which, for example, sulfur compounds, water vapor and solid particles are removed.



41. Figure: Crude oil refining in distillation towers [22] [4]

This is followed by fractionation, in which the various hydrocarbon components – such as ethane, propane or butane – are separated using modern cryogenic distillation and other advanced separation technologies. During the separation, the pre-treated crude oil is broken down into different fractions, such as gas, petrol, kerosene, diesel oil, and then lubricants and asphalt are produced from the remaining pakura (1.). The other part of the pakura (2) is used in a thermal power plant to produce electricity and heat for district heating.

42. Figure: In the event of a malfunction, both direct methane and incomplete combustion can result in extremely high PM, TOC and NOx emissions from the torch soot [4]

The amount of methane emissions depends primarily on the state of the technology, the measures taken to prevent leaks, and the quality of operation and maintenance.

43. Figure: : Dunamenti Power Plant, Százhalombatta [12]

44. Figure Gas and oil refinery [19]

4.2. Tiszaújváros

45. Figure: TVK: Tisza Chemical Plant [19]

Tiszaújváros is one of Hungary's significant natural gas processing centers. At the Tisza Chemical Plant (TVK), during natural gas processing, the crude gas is purified in several stages and converted into various chemical industry raw materials.

Methane emissions also play a key role in the total domestic greenhouse gas emissions. That is why Tiszaújváros is also placing more emphasis on the introduction of modern, leak-proof technologies and continuous emission monitoring in order to reduce methane emissions to the lowest possible level.

46. Figure: TVK power plant [19]

First, solid impurities and sulfur compounds are removed from the crude gas, and then, in addition to methane, other hydrocarbons such as ethane, propane, butane are separated.

These components are further utilized, for example in cracking, reforming or polymerization processes, which produce raw materials for the plastics industry (e.g. polyethylene, polypropylene). The heat and electricity demand of the technological processes is significant, which is also produced from natural gas to be processed.

During energy production, carbon dioxide, water, nitrogen oxide, soot particles, unburned hydrocarbons and carbon monoxide are also emitted by the flue gases.

During the technological processes, safe operation, the prevention of leaks and the continuous monitoring of emitted gases play a key role.

Using state-of-the-art equipment and automated systems, TVK strives to keep methane emissions and other environmental loads as low as possible, in line with domestic and international environmental requirements.

Nevertheless, leaks do occur. To avoid falls and fires, the composition of the indoor air is kept below the ignition concentration by continuous ventilation.

The gas that cannot be processed in the technology is flared.

4.3. Kazincbarcika

Kazincbarcika is also one of Hungary's most important natural gas processing centers, where methane emissions are also a significant factor in the total amount of greenhouse gases in Hungary.

At BorsodChem Zrt.'s site in Kazincbarcika, chemical industry technologies are mainly used to produce raw materials for the chlorine and alkali industries and plastics industries.

47. Figure: BorsodChem, Kazincbarcika [23]

The electrolysis production of chlorine gas and hydrochloric acid, as well as the production of vinyl chloride monomers, which is the raw material of polyvinyl chloride (PVC), play an important role in the plants.

In addition, there are aniline, toluene diisocyanate (TDI) and methylene diphenyl diisocyanate (MDI) production units, which are essential for the production of polyurethane foams and other plastic products.

In the course of technological processes, natural gas is used partly for energy production and partly as a raw material. Strict environmental and safety standards are applied in various chemical reactions, such as chlorination, cracking, and polymerization, to minimize methane and other greenhouse gas emissions. BorsodChem is constantly improving its equipment and automated systems to minimize technological leaks and production losses, thus contributing to the protection of the environment and sustainable operation.

In recent years, Kazincbarcika has been trying to minimize methane emissions through the use of modern leak reduction technologies and continuous monitoring, as "it is better to be safe than sorry" – in other words, prevention is always more profitable than subsequent damage control. Despite this, methane emissions from processing plants are still significant, so it is of paramount importance to continue the developments.

*48. Figure: BorsodChem: **left** coal-fired power plants that have already been shut down and are not operating; **right** the gas power plant [23]*

One of these developments is the replacement of the former coal-fired power plant with a gas-fired power plant. While the specific carbon dioxide emission of a lignite-based power plant is 1150 kg/MWh, that of a similar stand-by gas power plant is 480 kg/MWh.

The indirect climate impact and direct health damage from pollutant emissions are also significantly lower.

49. Figure: BC cracker catalysts, pilot plant

Catalysts are continuously being developed in Kazincbarcika for various technological processes, the use of which can significantly reduce the energy demand of the process and thus the amount of natural gas used.

5. Methane emissions from the distribution of natural gas to customers

Significant amounts of methane can also be released in the natural gas supply chain, especially when transported to customers – industrial, commercial or residential customers. The extent of the distribution networks, the age of the networks, and the condition of the connection and shut-off fittings all affect the extent of leaks. In Hungary, a significant part of the gas pipeline network was built decades ago, so continuous maintenance and reconstruction are key to reducing methane emissions.

The most common sources of methane emissions during gas distribution are connection points, distribution stations, pressure regulators, as well as household gas meters and internal networks. Leaks are often hidden; they can only be identified with special instruments and regular monitoring. Therefore, service providers are placing more and more emphasis on the use of modern leak testing tools and the introduction of rapid error correction procedures.

Advanced monitoring systems and automated control technologies introduced in the distribution phase will further increase security of supply while also contributing to the achievement of climate protection goals.

6. Methane emissions from natural gas use

In the end-use phase, whether for domestic, transport or industrial applications, methane escapes usually result from leaks in equipment, faults in connections or inadequate combustion processes. In Hungarian households, where natural gas is widely used for heating and cooking, old-style heat engines, gas boilers and gas cookers can be particularly prone to leaks.

In the industrial and energy sectors, methane emissions related to the use of natural gas occur mainly during the operation of gas engines, gas turbines and other thermal power engines. Inadequate maintenance, outdated equipment and technological leaks all contribute to increased emissions. As many small things go a long way, even small leaks can result in significant total emissions on a national level, so prevention, regular monitoring and the introduction of modern technologies are key to reducing methane emissions.

6.1. Methane emissions from domestic heat engines (I).

Methane emissions from household heating appliances such as gas boilers, gas cookers and water heaters can be traced back to two main causes: leakage of the equipment, and inadequate combustion processes. It is especially true for these devices that even minor faults can lead to bigger problems if we neglect maintenance. In the case of old-style devices, leaks are common, which often remain hidden, thus increasing methane emissions continuously, almost imperceptibly.

On the one hand, modern condensing gas boilers use less natural gas, and newer technologies already operate with significantly lower methane emissions. However regular inspection and maintenance remain essential. Since the use of natural gas is still widespread in Hungarian households, one of the keyways to reducing methane emissions is the replacement of old equipment, professional installation and the introduction of periodic technical inspections.

6.2. Methane emissions from gas engines used in transport (II.)

In the case of internal combustion engines used in transport, such as buses or trucks, methane emissions are mainly due to leaks, faults in connections or imperfect combustion processes of the engines.

Although natural gas vehicles have better CO_2 emissions compared to conventional diesel or petrol vehicles, methane leakage can be significant, especially in older or poorly maintained engines.

According to the Hungarian experience, regular technical inspections, engine control with advanced sensors and the use of modern sealing technologies can greatly reduce methane emissions in the transport sector. Preventive maintenance and the introduction of technological developments mean a more economical and environmentally friendly solution in the long run.

6.3. Methane emissions from gas turbines used in aviation (III.)

Methane emissions from gas turbines (jet engines) used in aviation are generally lower than those of natural gas-based onshore applications, as aircraft engines mainly use kerosene or other liquid fuels. However, methane emissions can occur during some special aeronautical developments, such as the testing of natural gas-powered gas turbines or the use of alternative fuels.

In these cases, methane emissions can mainly come from seal failures, leaks in fuel supply systems, or imperfect combustion. Nevertheless, methane emissions from gas turbines in aviation are currently considered a marginal environmental factor, but in the future, if natural gas or methane-based engines become widespread, stricter controls and the introduction of advanced monitoring systems will be essential to minimize emissions.

6.4. Methane emissions from gas turbines used in industry (IV.)

Methane emissions from gas turbines for industrial applications are a significant environmental challenge, as these equipment are often high-performance and operate continuously. The main sources of methane emissions can be worn seals, leaks at connections, and faults in fuel supply systems. Regular maintenance and rapid detection of leaks are particularly important in the operation of gas turbines in industrial facilities, as prevention always involves less cost and environmental impact than subsequent intervention. Monitoring systems with advanced sensors, automatic leak detectors and innovative sealing technologies already help minimise methane emissions in state-of-the-art industrial gas turbines. The replacement of outdated equipment, the introduction of modern technologies and the regular training of employees all contribute to the industrial sector's compliance with stricter environmental regulations. In the long term, these measures will not only reduce methane emissions, but also result in cost savings for companies through increased energy efficiency.

6.5. Methane emissions from gas turbines used in energy (V.)

Gas turbines used in the energy sector are primarily used for electricity generation, combined heat and power (CHP) generation, and to meet the heat demand of industrial processes. Methane emissions in these systems mainly come from leaks, faults in connections and leaks in fuel supply systems. During the continuous, high-load operation of gas turbines, even minor leaks can cause significant methane emissions, especially in the case of outdated or obsolete technologies. Modern gas turbines already use advanced monitoring and control systems, automated leak detectors, and advanced sealing technologies to minimize methane emissions.

Combined Cycle Gas Turbines (CCGTs) are one of the most widespread and efficient electricity generation technologies available today. In these power plants, the hot combustion products from the combustion of natural gas first drive a gas turbine, and then the flue gas from the gas turbine is further utilized through a heat exchanger to generate steam, which drives a second steam turbine. As a result, the efficiency of cogeneration plants is significantly higher, reaching up to 60%, while carbon dioxide and methane emissions are also lower compared to conventional gas turbines or steam-only systems. The lignite-fired 200 MW power plant unit of the Mátra Power Plant is also intended to be replaced with such electric power generation equipment. In terms of methane emissions, these power plants are of paramount importance: thanks to modern technologies, leaks in fuel supply systems, connections and seals can be minimized, and advanced monitoring systems enable rapid fault detection and intervention. However, regular maintenance, professional operation and the use of modern sealing technologies remain important in cogeneration plants to ensure that methane emission levels remain permanently low. The spread of this technology is a significant step towards reducing the environmental load and increasing energy efficiency, in line with the tightening domestic and international regulations. With regular technical inspections, periodic renovations and preventive maintenance, leakage losses can be significantly reduced. The use of quality components and continuous technological development contribute to keeping methane emissions in the energy sector low in the long term. Such investments not only help to comply with environmental regulations but also bring economic benefits through reduced operating costs.

7. Technologies for reducing methane emissions before the combustion in thermal power plants

7.1. Leak Reduction Technologies (A.)

Nowadays, there are a number of modern technologies available to reduce natural gas and methane leaks, which aim to minimize the environmental load and reduce economic and environmental losses. One of the most important steps is the use of advanced sealing technologies to significantly reduce leaks at connections, valves, flanges and other structural components. Modern sealants, such as polymers and composites that are resistant to high temperatures and chemicals, provide longer service life and greater reliability than conventional solutions. In addition, automated leak detection systems play a key role, enabling the rapid detection of leak points and continuous monitoring. The sensors can be infrared, ultrasonic or laser-based, which can detect the presence of even small amounts of methane, so maintenance professionals can intervene in time. Digitized data collection, remote monitoring, and predictive maintenance systems further increase the effectiveness of prevention, as they enable potential failures to be predicted and rectified immediately. In many cases, repairs are no longer worth it. In industry practice, the replacement of obsolete equipment with state-of-the-art components with low leakage losses and regular employee training to ensure that personnel recognize and properly handle leak hazards are becoming more common. Some technologies, such as pipe repair with composite covers, double-sealed valves, and the use of hermetic pumps and compressors, further reduce the risk of methane emissions. Continuous technological development, automated and predictive maintenance, and the use of quality materials combine to ensure that natural gas and methane leakage losses remain minimal in the long term.

7.2. Rapid elimination of leak points (B.)

Eliminating natural gas leak points quickly is vital to comply with environmental regulations and minimize economic losses. The possibility of rapid intervention is ensured by the use of reliable leak detection systems, remote monitoring devices and mobile diagnostic equipment. As soon as a leak is detected, on-site technicians must begin troubleshooting according to a pre-established procedure and with appropriate protective equipment. In practice, the use of modular repair kits (e.g. quick-release seals, temporary pipe clamps) has proven to be particularly effective, with which leak points can be isolated immediately and losses can be minimized. During the final repair, special attention must be paid to the replacement of defective connections or seals with modern, long-lasting components, as well as regular follow-up inspections. Such quick interventions not only reduce methane emissions but also contribute to increased operational safety and reduced operating costs. Timely detection and quick action will bear fruit in the long run, especially around leakage losses. Continuous training of employees, the development of rapid response units and the integration of innovative technologies all combine to minimize the environmental and economic damage caused by natural gas and methane leaks.

7.3. Rapid introduction of new technological innovations (C.)

The rapid introduction of new technological innovations is key to reducing and preventing natural gas leaks more effectively. The latest developments include intelligent, networked sensor systems that can immediately detect even the smallest leaks with real-time data collection and analysis. These systems use artificial intelligence to analyze leakage patterns, allowing maintenance interventions to be planned and more targeted. Automated inspections with drones and ground robots are gaining ground, which can quickly and safely detect potential leak points even in hard-to-reach places. The use of new, advanced sealants and self-healing coatings is another important step in preventing leaks, as these materials can dynamically adapt to structural movements and temperature fluctuations.

The introduction of wear simulation tests designed with digital twin technology enables continuous, virtual monitoring of the entire natural gas infrastructure, allowing system operators to predict wear or failure of critical points. Industry collaborations and knowledge sharing accelerate the spread of innovations, while continuous training of employees ensures that the introduction of new technologies is carried out smoothly and effectively. Rapid innovation responsiveness means a long-term competitive advantage and sustainable operation in the energy sector.

7.4. Rapid detection of methane emissions and establishment and maintenance of an effective legal, punitive and restorative enforcement system (D.)

Rapid detection and effective management of methane emissions requires the development of a comprehensive legal, punitive and restorative enforcement system. The first step is to build a nationwide unified monitoring network that provides real-time data on emission points, allowing authorities to intervene quickly. In addition, the regulatory environment should be designed in such a way that the reporting and monitoring of methane leaks is mandatory for all relevant industry actors, with strict penalties in case of delayed or incomplete reporting.

The system of punitive measures may include fines, suspension of operating licenses, or even a temporary halt to operations if the leaks are not eliminated within the time limit. The aim of the restoration implementation scheme is to oblige polluting companies to repair damage and restore the state of the environment, for example by cleaning up contaminated sites or using new technologies. Regular audits, independent audits and public reporting make processes transparent, increasing social control and industry responsibility.

In order to ensure effective implementation, it is advisable to establish rapid response control units with special training and modern measuring equipment. These units are able to intervene immediately in critical situations, minimizing the environmental damage caused by methane emissions. Rapid recognition and action can significantly reduce damage.

Cooperation between the state and industry, continuous legislative development, and the incorporation of community and international experience ensure that methane emissions can be kept under control and that sustainability goals are achieved.

7.5. Application of modern flue gas after-treatment systems used in and after thermal power engines (E.)

The introduction of modern flue gas after-treatment systems in and after thermal power plants offers significant progress in reducing air pollution and achieving sustainability goals. These systems, such as catalytic oxidation units, selective NOx catalytic reduction (SNCR) processes, or advanced dust separators and filters, are capable of effectively neutralizing harmful components in flue gases, such as solid particulate matter, nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOCs and TOCs).

Through modern post-treatment technologies, methane and other hydrocarbons are fully burned, thus minimizing greenhouse gas emissions. Automatic system control allows you to maintain optimal operating conditions while reducing maintenance requirements and operating costs. It is particularly important that the operators of thermal power engines continuously develop and maintain their flue gas after-treatment systems, adapting to the stricter environmental regulations.

The use of modern flue gas after-treatment technologies not only reduces the environmental load but also contributes to the long-term economic and safe operation of the plants. The integration of such developments into existing systems can provide a competitive advantage in the market, while also setting a positive example in terms of social responsibility. Society is becoming more environmentally sensitive. Increasingly, it is about buying from service providers that are at the forefront of protecting the environment. The facilitation of the selection of such service providers could also be supported by a trademark system that can be applied for.

8. Proposals for research, development and introduction of further new technical possibilities

The introduction of digital twin technology creates an opportunity to continuously monitor the operation of energy systems in real time, predicting the wear and tear, failure or decrease in the efficiency of equipment. This optimizes the maintenance process, reduces unexpected downtime and extends the service life of your equipment. Such systems support data-driven decision-making, which can provide a competitive advantage for industry players in the long run. It is recommended to use artificial intelligence (AI) and machine learning to predict emissions, leaks and other critical events, as well as to increase the efficiency of energy processes. AI is able to quickly analyze large amounts of data to support rapid intervention, reduce environmental damage, and help achieve sustainability goals. The integration of circular economic principles into energy systems is a significant step towards sustainability. These include the utilization of energy from waste, the gasification of biomass and communal waste, and the development of synthesis gas sharing systems. These technologies reduce environmental impacts, increase energy efficiency and create new opportunities for local communities. It is recommended to develop active, autonomous buildings and facilities capable of fully recovering and decarbonising low concentrations of methane leakage from extraction, transport, processing, storage and distribution. This will not only reduce emissions, but also increase energy efficiency, which will bring economic and environmental benefits in the long run.

8.1. Introduction of ultra-low exhaust resistance, reliable, long-maintenance-free exhaust gas after-treatment processes

50. Figure: Flue gas treatment systems with an exhaust resistance of up to 2-9 mBar OEM conventional systems can result in fuel savings of up to 15-25% compared to 250-450 mBar counter-pressure [4]

Ultra-low exhaust resistance, reliable and maintenance-free operation for a long time Exhaust Gas Treatment Systems Its implementation at a low cost level and within a few years is key to modern energy systems. These processes allow the exhaust gas flow to take place with minimal resistance, so they do not reduce the efficiency of the power plants while ensuring the efficient removal of harmful substances. The use of such systems reduces the need for maintenance, enables stable and safe operation in the long run, and significantly contributes to the fulfilment of stricter environmental standards.[23]

51. Figure: Performance results of high-power gas and diesel engines from Proof-of-Concept pilot with ultra-low exhaust back pressure [4]

Through technological advancements, materials and structural solutions are used that can withstand high temperatures and corrosive gases while maintaining an ultra-low pressure drop.

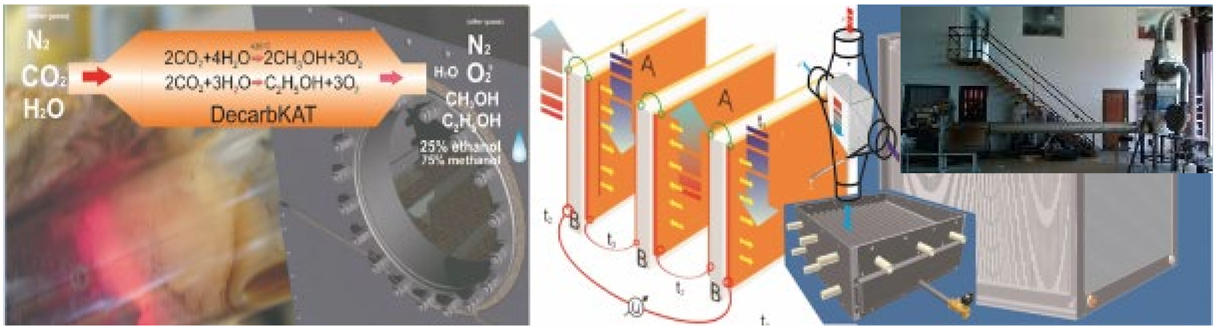
As a result, the service life of the systems is extended, operating costs are reduced and the environmental impact can be minimized. Innovative solutions pay off in the long run in the name of sustainability and economy.

8.2. Research, development and rapid implementation of ultra-low emission catalytic incandescent and catalytic decarbonization processes

"The complex retrofit monitoring and zero-methane catalytic flare, ventilation and leakage utilization system." RDI topic proposal. The development of ultra-low-emission catalytic on-bulb and catalytic decarbonization processes is of paramount importance for the realization of sustainable energy systems. These technologies make it possible to greatly reduce pollutants in exhaust gases and other emissions, such as hydrocarbons, carbon monoxide, volatile organic compounds, while not compromising the energy efficiency of the system. During catalytic on-bulb processes, special catalysts promote the rapid and complete oxidation of harmful components, so that a minimal of pollutants are released into the atmosphere.

52. Figure: Catalytic bulbs [4]

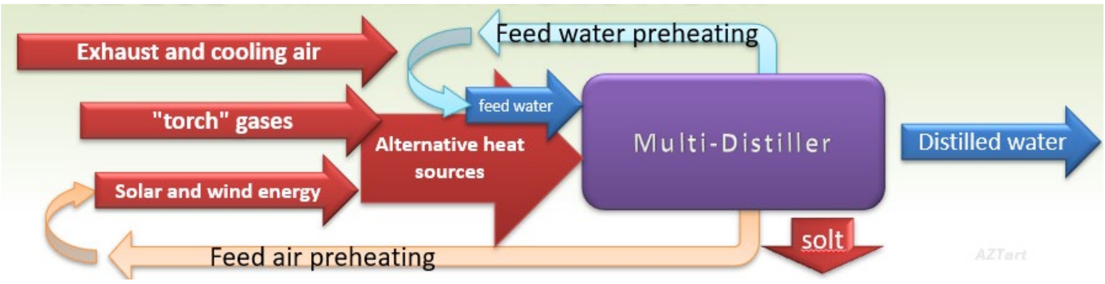
Catalytic oxidation reactions taking place faster than the available reaction time during the heat of NOx formation, above the excess air for soot formation, can open a completely new opportunity in the energy sector. This solution eliminates soot and nitrogen oxides and oxidizes all methane without residue. There are no unburned hydrocarbons or carbon monoxide left. During PoC practical measurements, all harmful substances remained ZERO in most cases, but in all cases below 5 mg/Nm^3 emission value. Ultra-low emissions can be maintained over a very long service life (180,000 guaranteed operating hours). The specific carbon dioxide emissions are 30-40% lower than in the case of BAT OEM gas burners. During research and development, special attention must be paid to increasing the life of catalytic converters, optimizing operating temperatures, and reducing operating costs. Catalytic decarbonisation processes make it possible to further reduce carbon dioxide and other greenhouse gas emissions, which contributes to the achievement of climate protection objectives. The rapid and widespread introduction of the procedures will help Hungary to be at the forefront of energy innovation, thus setting an example for other players in the region.



53. Figure: The decarbonization catalyst and thermoelectric heat exchanger [4]

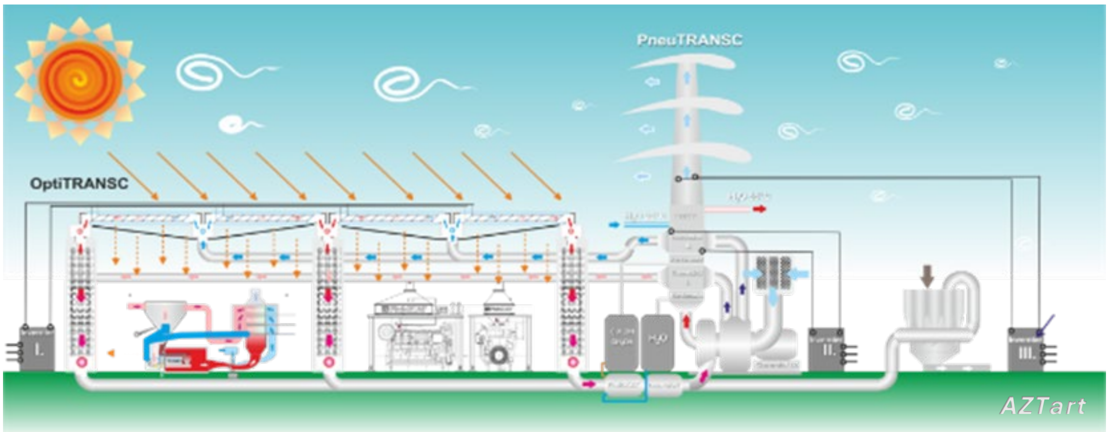
The carbon dioxide content of the flue gas entering the decarbonization catalysts at a temperature of 475°C, with a CO_2 concentration of 10-12% and a content of 0-2% oxygen and saturated water vapor decreases below 100-200 ppm when exiting the catalyst. Since this value, which has already been measured in practice, is lower than the CO_2 content of 413 ppm (0.87 grams/Nm) in ambient air, the technology can be a solution for retrofit and quickly recouped applications of negative carbon footprint processes to any heat engine. From there, any thermal engine can be converted into a CO_2 separator and a renewable source of alcohol, replacing fossil energy sources with the produced alcohol. In carbon-based structural materials (not underground, but underground), in our built environment, in the structural material of our machines, bridges, ships, trains, stored in cycles of up to 50-100 years and recycled repeatedly, it can be kept in a "Carbture" cycle, just like nature does! But in a different way compared to the current solutions, with a profit. If it is not only environmental sensitivity or legal coercion that promotes the app, but also profit, it spreads quickly. It is recommended that research institutes, industry and regulatory authorities work closely together to introduce new technologies, facilitating the rapid industrial application of laboratory results. During the developments, it is expedient to launch pilot projects, based on the experiences of which the widespread adaptation of technologies can be accelerated. Rapid innovation brings significant economic and environmental benefits in the long run.

8.3. Construction of gas-tight, zero-methane, active, autonomous buildings for critical structures for extraction, transportation, processing, storage and distribution with full heat utilization and decarbonization of low-concentration methane leakage on a catalytic over-glow flare



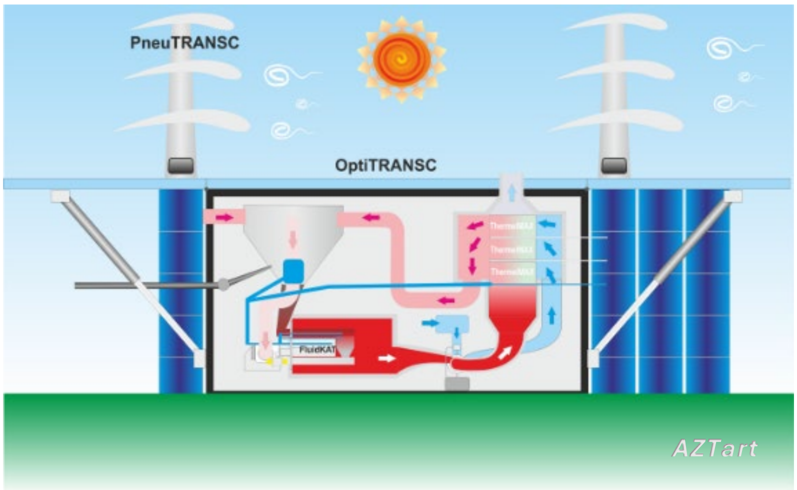
54. figure: Multi-distillation steam generation and condensation heat utilization

By utilizing multi-distillation steam generation and condensation heat, continuous heat demand can be significantly reduced. The "waste energy" of gas extraction so far can also be used as a source of steam generation energy. As an additional source, renewable solar and wind energy can be utilized from the solar surfaces of buildings and containers with active pavement. With the alternative optimal, environmentally conscious combination of the above sources, readiness, continuous and safe operation can be ensured.



55. figure Complex monitoring and modular separation and conversion of methane emissions from natural gas extraction, transportation, storage, distribution and use [4]

The zero-methane, gas-tight design of critical energy structures, such as gas extraction, transport, processing, storage and distribution facilities, is essential for environmental protection and sustainable operation. The active and autonomous systems of such buildings are able to continuously monitor, detect and manage low-concentration methane leaks, thus minimizing losses. The use of catalytic incandescent flares allows us to utilize the full thermal energy of the evanescent methane, while decarbonization also significantly reduces carbon dioxide emissions. It has energetic benefits and also economic benefits, in addition to reducing losses, the autonomy of the system increases safety and reduces the need for maintenance. Modularly expandable, retrofit flares from multicyclone gas soot separation with high sulfur content for the production of raw materials for cement and rubber production. The flare's flue gas and the gas-tight active e.g. (solar panel) covering of structures for extraction, transport, processing, storage and distribution. If the catalytic incandescent is fed together with the low-concentration methane leakage, flare flue gas and air generated from ventilation and the catalytic decarbonization is ensured with the released so far – loss heats, then the entire methane emission can be converted into recyclable alcohols. The parade buildings and containers of gas extraction can be built from special panels, and they can even be tiled afterwards. Window and wall-mounted solar collectors with active optical transmission convert solar energy primarily into hot air. The 400-500°C 6x6 mm points of the optical transmission, arranged in a matrix, heat the infector light absorbers placed inside the panels. We heat solid heat stores with the hot air, storing the heat in them for the time when the sun is not shining. The primary source of heat energy of the steam generator is 800-1050 kW/m2 per hour in the summer and 250-300 kW/m2 in the winter, which is used to heat the equipment. In most cases, the methane content of ventilated air does not reach the concentration of ignition. If we suck the air necessary for operation into the thermal engines from the energy structure, it can be completely oxidized by leading all the leaks into the catalytic glow chamber. It is also possible that the pipelines will also receive a casing, and the compressor stations will suck the air necessary for energy production from the pipelines and casings. This allows the entire pipeline system to be converted to zero methane emissions with a high degree of safety, even retrofitting.

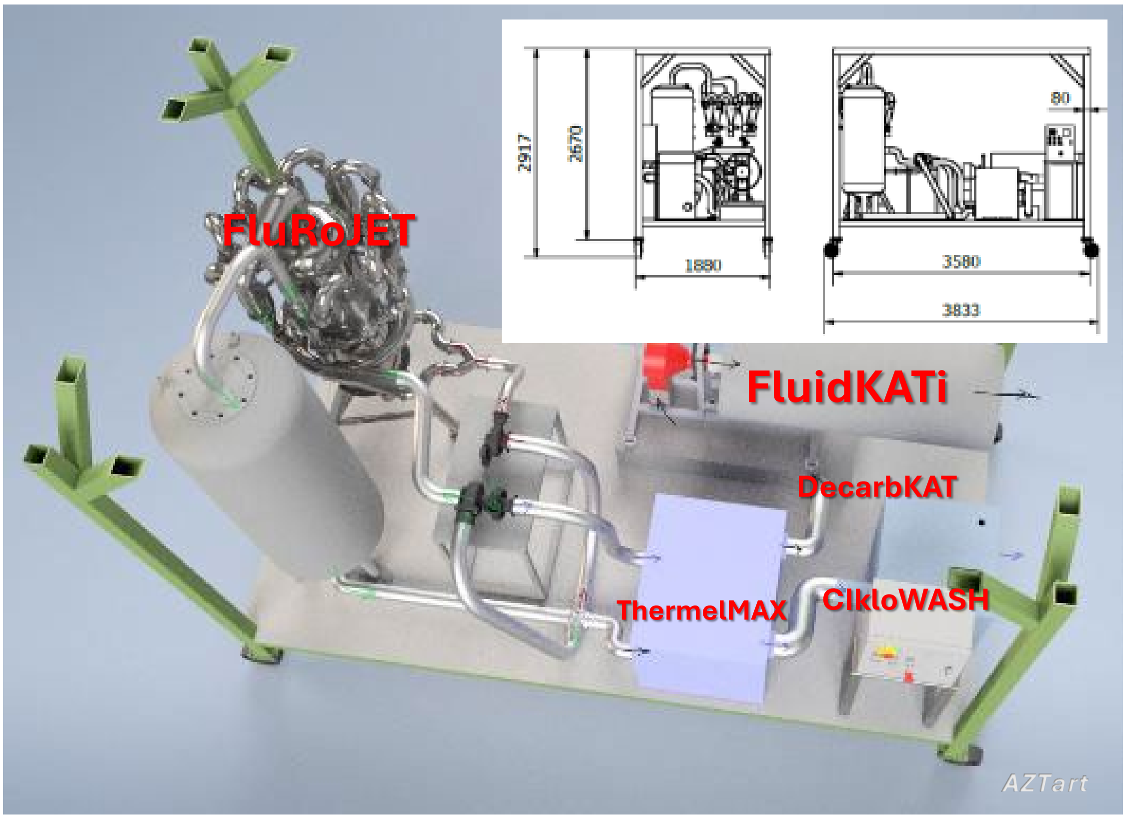


56. Figure: Catalytic flare [4]

Ventilation gases from gas extraction and processing cannot be ignited on a normal flare, but when sucked together in the feed air by a catalytic incandescent bulb, methane can be oxidized to carbon dioxide and water vapor with ultra-low (zero) emissions. The unutilized loss heat is sufficient to provide the energy needs of the catalytic decarbonization reaction. During decarbonization, ethanol, methanol, dimethyl ether are formed and oxygen is released.

In the case of cascade, containerized group designs, retrofit can also be set up at the site of natural gas extraction, transportation and processing, to meet any ventilation leakage methane gas processing needs.

The air supply of the container is the collection of ventilated gases from the interior of natural gas extraction, transport and processing equipment and their casing or from inside industrial buildings or from under the casing of pipelines. It will not flow out into the open air with the air, but will be completely oxidized without residue when it enters the catalytic glow chamber with the sucked air. When using a decarbonization catalyst, carbon dioxide can be completely converted into alcohols and selectively condensed in the thermoelectric heat exchanger. In Hungarian innovation practice, technologies that integrate the oxidation and heat recovery of low-concentration methane leaks with catalytic incandescent into the energy supply of buildings are increasingly coming to the fore. These systems are constantly improving themselves, adapting to changing environmental and operating conditions. The complete oxidation of methane does not produce soot or other harmful by-products, and the energy released can be recycled for heating, hot water production or even electricity generation. Such autonomous buildings can also set an example for other actors in the region to achieve zero emissions, contributing to the achievement of international climate protection goals.

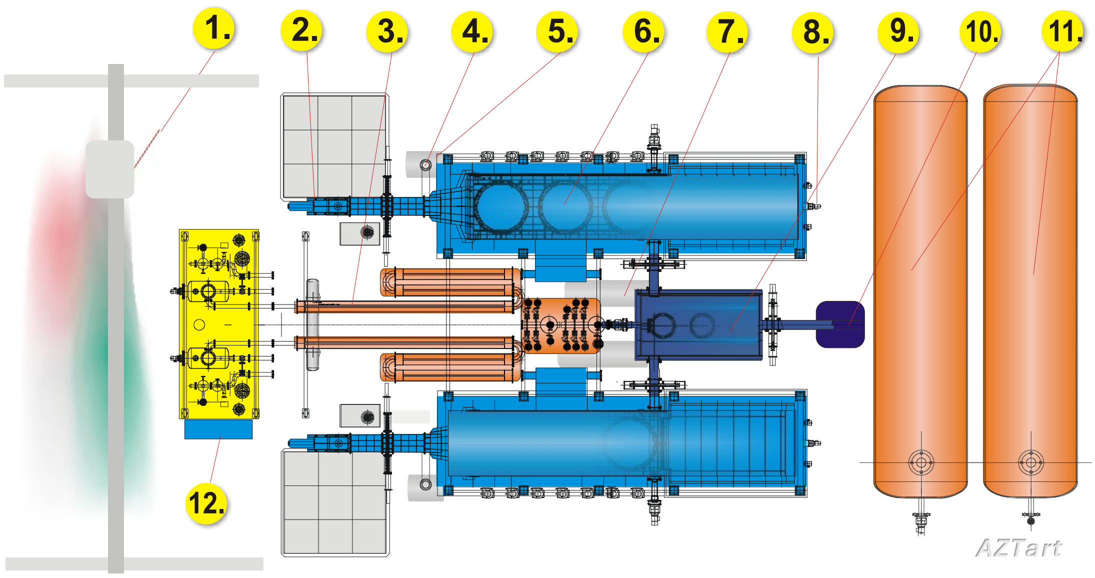


57. figure: Further developed "CATALYTIC (FTcFi) TORCH and gas soot separator" equipment [4]

In the above version, the FFDT can be operated interchangeably with natural gas instead of flares. The technological (contaminated) natural gas to be burned in a pre-chamber with a low excess of air is converted into gas soot. The soot is dryly separated in a multicyclone for several stages, then the syngas is cooled back in a dry synthesis gas-air heat exchanger and washed convolutely in a piezo cyclone washer. Sulfur rich and other solid carbon black (e.g. fine iron and other metal oxide powders) is an excellent addition to rubber production. In addition to carbon dust, these additives are needed to produce modern, high-quality tires. The residual heat is transferred to the catalytic bulb by the used, ventilated back cooling air. The synthesis gas separated from the added soot is now clean, dust-free, so it can be fed to the catalytic incandescent.

With the catalytic decarbonization of dual carbon, black carbon, black torch, and catalytic glow chamber presented above, both flare gases and ventilation gases can be separated in one pass and converted into useful materials.

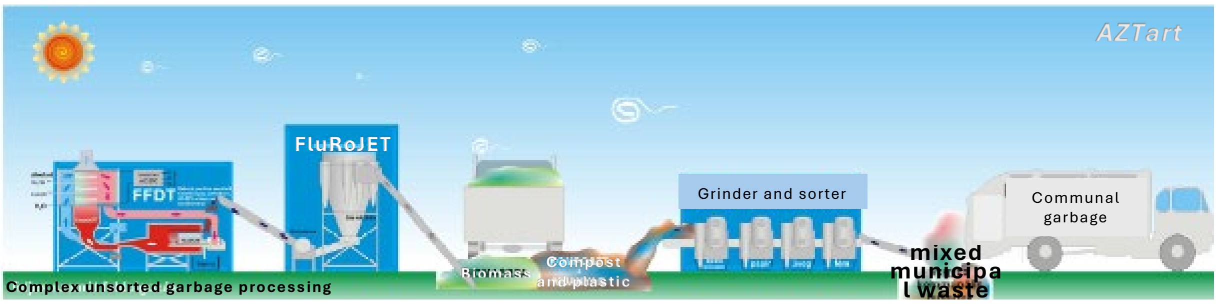
8.4. Communal waste and biomass gasification and synthesis gas sharing system



58. Figure: PCP municipal waste (sorted plastic) processing system [24]

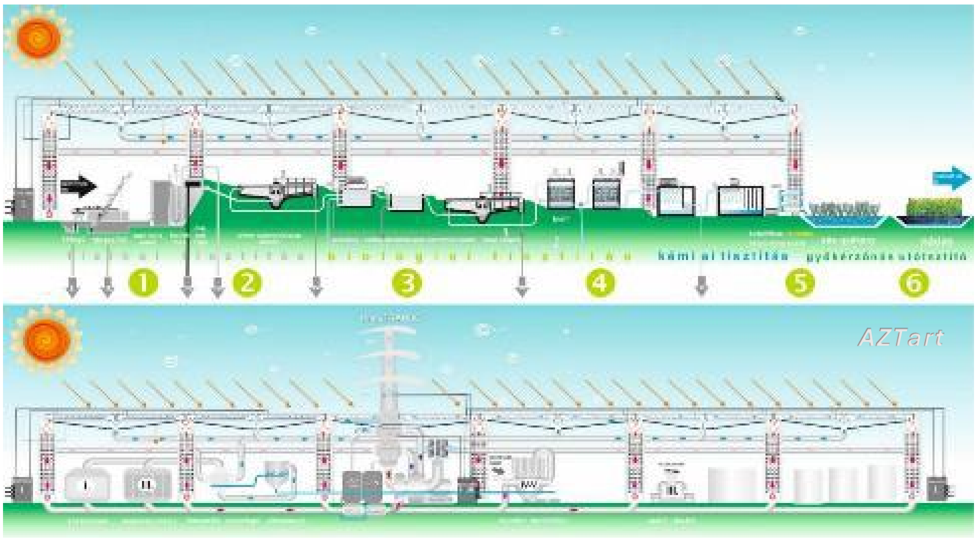
1. Raw material storage **2.** manual feeder **3.** Distillation system **4.** Chimney **5.** Heating System heat exchanger **6.** reactor **7.** Distillation system heat exchanger **8.** Heating system **9.** Cleaning system heat exchanger **10.** Final storage of the cleaning system **11.** Finished product storage **12.** Control and control system.

Today is the most difficult technical task of waste management. The material and energy recycling of plastics around us. In the PCP system, using a thermocatalytic process, approx. 70 % of the plastic mass flow (liquid plastic oil can be converted into "fuel oil" form), can be mixed with standard B7 gasoline, diesel or kerosene, and can reduce the fossil share of the fuel. approx.: 20 %. Synthesis gas with high methane content approx. 7 % solid mass usable as bitumen and approx. 3 % decomposes into water vapor.



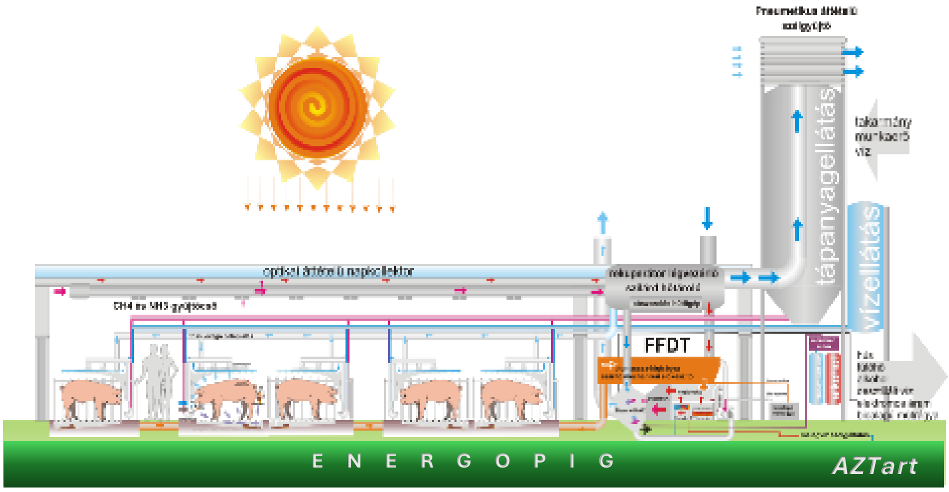
59. Figure: FFDT in the material and energy processing of unsorted mixed municipal waste [4]

The FFDT equipment can be set up with different processing capacities (1x1.5x2m) household-sized, containerized, community processing capacity, industrial cascade or individual assembly size where waste is generated, and the produced syngas can be collected, stored and distributed through the natural gas network. The essence of the communal waste and biomass gasification and synthesis gas sharing system is that it produces syngas from solid waste and biomass at high temperatures, in an oxygen-poor environment, which can be used as a valuable energy carrier. During catalytic gasification, organic matter and a mixture of unsorted municipal waste are formed into a gas mixture containing hydrogen, carbon monoxide and a significant amount of methane, which is completely converted into methane gas by catalytic reformation. The synthesis gas is even equivalent to the quality and energy content of pipeline natural gas.

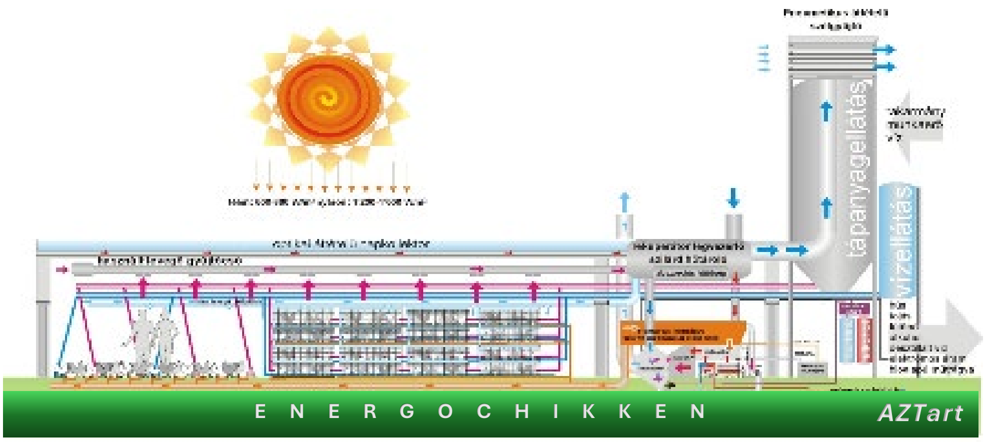


*60. Figure: **1.:** Grid waste filtration, physical sedimentation and separation of sewage sludge; **2.:** Activated sludge biological separation; **3.:** Biophilic, chemical, catalytic ionizer, UV light separation [4]*

In agriculture, it is not only the accumulation of slurry on livestock farms that is a problem. Significantly more methane can be measured in the breath of animals than is emitted from the slurry.

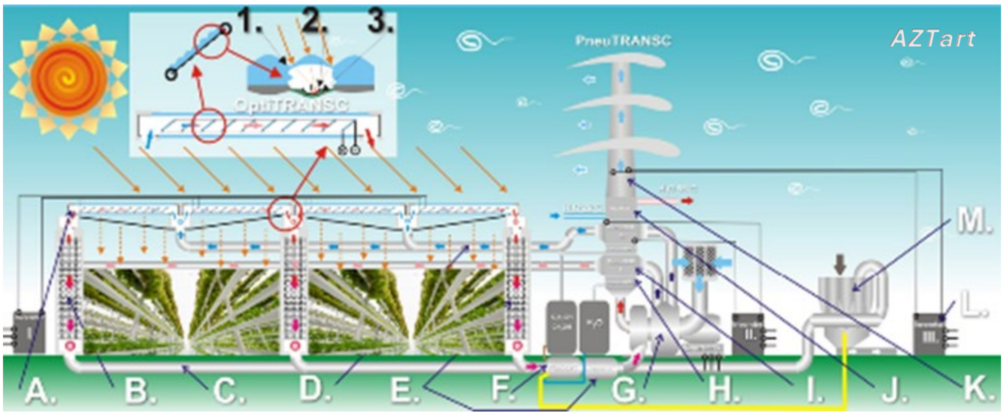


61. Figure: FFDT-ZEEP ultra-low methane and CO_2 emission pig farm [4]



62. Figure: FFDT-ZEEP ultra-low methane and CO_2 emitting poultry housing [4]

Such innovative systems contribute to the circular economy and the development of sustainable energy supply and waste management. With a vertical crop growing system (VNT) implemented in an active autonomous system, the plants only absorb carbon dioxide 24 hours a day, every day of the year. There are no night-time carbon dioxide emissions, and the leaves that fall in autumn do not degrade, emitting methane, carbon dioxide and nitrate monoxide into the atmosphere.



63. Figure: FFDT-ZEEP VNT [4]

The notations used in the figure are: A.: optical solar collector with full roof and side wall surface; **B.**: solid heat storage; **C.**: air collection system; **D.**: vertical plant growing cabinets with LED illuminated grow trays; **E.**: with a controllable nutrient supply system on our tray; **F.**: FluidKATi, catalytic bulb; **G.**: e-turbo; **H.**: DecarbKAT catalytic decarboniser; **I.**: ThermelMAX, thermoelectric heat exchangers; **J.**: HeatMAX – DewKAT residual heat treatment absorption water separator; **K.**: pneumatic gear wind collector; **L.**: Inventer electric current regulator and converter; **M.**: FluRoJET dryer and gasifier.

The introduction of ZEEP-VNT negative CO_2 emission technology represents the highest negative CO_2 sequestration capacity. More than 70% of the energy produced in the world is used in buildings. It is possible to build livestock farms with a ZEEP active, autonomous building energy solution with vertical crop production and closed negative carbon dioxide emission systems, in which carbon dioxide emitted by animals and humans and the entire solid and liquid waste mass stream can be separated and solar and wind energy collected on the entire surface of the building can be converted into chemical renewable standby energy.

ZEEP technology promises food autonomy, so our settlements can be self-sufficient without outdoor production[13]. 70% of the world's energy consumption is tied to buildings. In 2023, global fossil carbon dioxide emissions amounted to 36.8 billion tons (GT). By 2024, it exceeded 40 GT. Compared to the Industrial Revolution (278 ppm), there is 1'052 GT more (412 ppm) more carbon dioxide in the atmosphere. If we make our buildings active, the lack of fossil fuel-source carbon dioxide consumed so far to operate the buildings can reduce global carbon emissions by up to 70%. The more energy produced and stored in carbon-based energy carriers; the less fossil energy carriers will be needed. By using renewable energies collected from the carbon dioxide sequestered above the operational needs of buildings, it is possible to make the use of carbon dioxide fully circular globally by operating our traditional thermal power engines by operating ethanol, methanol, di-methyl ether (EMD) alcohols and green re-methane (GRM) forms. Just as nature uses it. We must acknowledge that life on Earth is carbon-based. If we can produce the food necessary for the supply of humanity on 1 hectare instead of 300 hectares of arable production with intensive crop cultivation tools on renewable energy sources in our buildings, then today's agriculture can return its monoculture areas to nature, and forest and game

[13] *ZEEP, NEXT-AGRO, ZEEP-VNT, ENERGOPIG)*

management can be carried out in part of it. 1 hectare of corn binds 2 tons/year of CO_2 per year. 1 ha of pine forest 12 tons. Nature's natural ability to absorb carbon dioxide can be restored.

The structural material of life on Earth is also carbon-based. We also must learn it again. Climate catastrophe cannot be avoided by taxes and penalties. There is a climate out! The businessmen who move the world would compete for participation in the next renewable energy "gold rush", if energy stored in renewable CO_2 and carbon-based structural materials are cheaper for the customer and generate greater profit for the service and trading producer. The buildings are consciously built from carbon-based building materials. Over the past 228 years, the carbon dioxide accumulated in the atmosphere can be stored permanently – with benefit – in natural (wood, bulrush, reed, straw, etc.) and artificial carbon fiber micro-structured composite structural materials, and by using traditional lime and cement building materials produced **with negative carbon dioxide emissions**, as well as steel and other metal structures. On the natural gas network built up in the last century, natural gas can not only be distributed, but also synthesis gases can be collected. The system and the service providers will remain, only the entire communal waste and biomass in Hungary can be converted into renewable synthesis gases. One of the main advantages of the system is that it can process waste and biomass of different compositions, thus significantly reducing the amount of waste that ends up in landfills. The heat generated during the operation of the system can also be recycled, thus increasing energy efficiency. By applying this technology, not only can the environmental impact be reduced, but new economic value can also be created from waste. Thanks to its modular design, the gasification system can be easily adapted to existing energy or industrial facilities and can even be used at the decentralized municipal level. **W-SyngasGRID** is the concept of a waste recovery synthesis gas sharing network. According to which we process waste where it is generated. We do not transport, sort, or dump waste, but rather process what has been deposited so far. To this end, processing units with purposefully settled processing capacity are placed in a decentralized manner. 85-97% of the mixed unsorted waste mass stream can be converted into pipeline natural gas quality and energy equivalent synthesis gas and fine ash. In the last century, the natural gas pipeline network and storage capacity have been built at huge costs.

Through the pipeline network, the gas can not only be transported to the receiver, but the synthesis gases can also be collected and stored. To do this, the synthesis gas must be converted and purified to the quality characteristics applicable to natural gas. In 2023, approximately 4.7 million tons of municipal waste was treated annually in Hungary. Another 12 million tons are agricultural and forest by-products as biomass. Excluding industrial waste, 12-13 billion Nm^3 of natural gas energy equivalent synthesis gas can be produced from nearly 17 million tons of decentralized solid waste. Most of the waste and biomass mass stream is generated in the summer months. In this case, there is no heating, significantly less natural gas is consumed. In Hungary, 4.5 billion sqm^3 of natural gas can be stored annually in underground storage. The natural gas network is used to collect and store unused syngas from consumers. In Hungary, in 2023, less than 9 billion Nm^3 of natural gas was consumed and natural gas production was less than 2 billion Nm^3.

According to the above figures, if W-SyngasGRID is implemented, Hungary would not have to purchase expensive and uncertain foreign fossil source natural gas but would have about 5-6 billion Nm^3 of renewable source synthesis gas with a methane content of over 99% (practically considered negative carbon dioxide emissions)[14]. If 52.6 GT of carbon dioxide per year is stored - with good profit - in negative emission structural materials, CARBTURE and kept in circulation for up to 50-150 years, then the CO_2 concentration of the climate and atmosphere can be restored in as little as 20 years.

[14] FFDT-ZEEP *Retrofit Conversion Concept of Coal Power Plants)*

9. Summary conclusions

Hungary has one of the densest natural gas networks in Europe. More than 90% of potential gas users have access to gas services. The largest diameter pipelines form the main transport backbone of the country, connecting import entry and production points with domestic storage and distribution systems. These pipelines are able to ensure Hungary's peak winter consumption, which can be up to 60 to 70 million Nm^3 of natural gas per day. The entire gas network is more than 160 thousand kilometres[15] long. 5.9 thousand km is the transmission pipeline and 81 thousand km is the distribution network up to the consumers' plot boundary. At least 76 thousand km of pipelines connect natural gas sources from the plot boundary to the gas appliances to more than 3.4 million residential and more than 200 thousand industrial gas consuming equipment.

The conveyor and distribution pipes are made of high-strength steel with a corrosion protection coating and an active cathodic protection system. This protects them from corrosion and ensures that the lines will operate safely for decades, even in adverse soil conditions. The vast majority of the Hungarian natural gas transmission and distribution transmission line system runs underground, about 95-97% is invested in the ground. Nearly 400 independent underground pipelines have been laid underground under agricultural areas, near settlements or next to nature reserves, and only minor sections (passages, around compressor stations, special structures) are about 350 km long on the surface of the earth.

The reliability of the detection of LDAR methane emissions from underground pipeline sections is greatly limited by the gas emission isolation of the earth and the homogenization of the emissions, as well as the cross-sensitizing methane emission of biomass degrading on the earth's surface. The Hungarian natural gas transmission pipeline system has a history of more than 76 years: the first high-pressure pipeline was built in 1949, so the foundations of the system are more than seven decades old, while the average age of the pipelines today is about 38 years!

The gas pipes are welded or screwed together from pieces between 80 and 1400 mm in diameter, between 2 and 10 meters, through the flanges formed on them. Approximately 32 million pipe connections have been established on the entire pipeline network and approximately 15 million fittings have been installed up to 3.7 million gas-consuming devices. Gas-consuming devices also have several connectors and fittings.

There are more than 50 million places on the entire Hungarian gas network, up to the end-user equipment, where the gas tightness of the system deteriorates over time and with the aging of structural and insulating materials, and leaks can occur. In addition, methane can continuously flow into the air through microcracks in the pipe wall that make up any part of the entire pipe length[16] .

Methane can flow to the outside through leakage gaps depending on the internal pressure. The maintained pressure is 40 - 75 bar in the conveyor lines, 1 - 4 bar in the distribution lines, and 20 - 30 mBar up to the gas appliances. Large quantities of gas can escape freely into the air in a short period of time through a leak gap in high-pressure sections that account for 3.7% of the pipe length.

At the gaps in the medium-pressure supply system, which accounts for about 50.5% of the total gas pipe system, leaks are possible in proportion to the lower pressure, but overall, in larger quantities and more difficult to detect. Pressures maintained over at least 45,8 % of the length of the gas network have the lowest specific leakage.

On this pipe-length system, we are practically not aware of Planned Preventive Maintenance (TMK), only the number of subsequent repairs following the detection of an event-based leak can be compared with the data of the natural gas system service providers. Based on these, it is likely that the specific leakage characteristics of the private network natural gas network are up to 2.5 times higher than those of the service providers TMK. systems. The same is true of private gas appliances in the field of micro-leaks.

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[15] *Such a long pipe system would go around the ground even twice.*

[16] *To use a strong analogy, but it's like trying to carry water with a broken sieve in several places!*

It is already a serious problem and requires immediate decommissioning measures if[17] the smell of natural gas is already felt!

During extraction, the carbon dioxide content of the mine gas can be up to 5 - 42%. The extraction of "lean gas" with a carbon dioxide content above this is no longer economical. Such mine gas is not processed – even if it enters the market at a higher rate – mining gas with a carbon dioxide content of more than 30%. In the best case, it is pressed back into the well to increase extraction or burned with a torch, but the flame of the mine gas cleaning residual torching of mine gas with a low methane content – below the ignition concentration – is uncertain, easily extinguished, and its operation is dangerous for accidents. In this case, it is ventilated outdoors together with carbon dioxide. Heavily polluted gases left over during the processing of natural gas cannot always be flared, and in the event of a malfunction, if the amount of methane that exceeds the burning capacity of the torch should be burned, the unburnable amount is also released into the open.

In 2024, more than 15.9 billion Nm^3 of natural gas was transported through this gas network and 6.4 billion Nm^3 was stored in domestic storage facilities, of which 6.6 billion Nm^3 was transited, 1.4 billion (expected to be 1.98 billion Nm^3 in 2025, following the government's measures to promote energy independence) were collected from decentralized domestic natural gas extraction sites. Hungary used 8.5 billion Nm3 of gas, of which it purchased 7.7 billion Nm3 of gas, mainly from Russia, of which 0.6 billion Nm3 was resold. This makes Hungary the second largest importer of natural gas in Europe. France is the first with 10.4 billion Nm3. Hungary is one of the most exposed[18] countries to Russian imports in Europe.

The methane emissions in Hungary during the extraction, transport, storage and distribution operations, the sum of the different proportions and types of emissions (leakage, ventilation, flaring) and the methane emissions of processing and use losses for each operation have been determined weighted by natural gas volume flow characteristics and are set out in the (Annex 4.sz. 16. table on 75). **Natural gas production is 0.056, transportation is 0.52, storage is 0.13, processing: 0.31, distribution: 0.25, consumption: 0.15, total: 1.05 billion Nm^3 of methane emissions are emitted to the environment.** Approximately 60% of Hungary's natural gas consumption was used for electricity and district heating in the energy sector, 10% in the chemical industry and 30% in residential heating and small businesses. Both processing and use have methane and non-methane hydrocarbon emissions (NMVOCs).

The specific TOC (CH_4+NMVOCs) emissions of flares, boilers, gas turbines and gas engines and their absolute emission values proportional to natural gas consumption differ according to the types of thermal power plants and performance categories. The equivalent emissions of methane and methane from natural gas processing (0.31 billion Nm^3) and use (0.15 billion Nm^3) are also significant, because in both cases there are detectable leaks and ventilation, and the burned hydrocarbons also flow freely into the open air with the flue gases.

The source of the data was collected on the basis of statistics published on the basis of the self-reported data of the system operators. During 10 independent random checks, methane leaks were detected in 8 cases and at different locations, which were more significant than the reported data. Based on the measured values, it is likely that based on statistical data, the actual methane emitted by natural gas in Hungary is aggregated, it may even be significantly higher than the ones included in the table.

The world economy requires more and more energy. Gas and oil producers are interested in making as much profit as possible. All the findings of fact are brushed off them. As long as the gigantic profits are realized in the sale of natural gas, the situation will not change but rather worsen with the expansion of energy consumption. In addition, the huge capital accumulated in the energy sector is significantly inertia. Until the investment in fossil energy extraction pays off, the extractors maintain the conditions for the possibility of return until the nail break. Fossil energy use has practically doubled in the last 33 years. The expansion of fossil energy and the profits that can be extracted from it are fueled by the demand of users. Users are trying to get energy at the

[17] *Mercaptans (thiols): e.g. tert-butyl mercaptan (TBM), ethyl mercaptan (EM). Sulfides: e.g. dimethyl sulfide, dimethyl disulfide. These compounds have a very low odor threshold; they can be detected even at a concentration of a few ppb (parts per billion).*

[18] *Among European countries, those with low own production and high dependence on Russian gas are the most exposed to natural gas imports: the Czech Republic 100%, Slovakia 100%, Hungary 95%, Austria 90%, Germany 90% and Italy 85%.*

lowest cost, as far as they can. Users are becoming more and more environmentally sensitive. The above italicized paragraphs are supported by the analysis of methane emission data from natural gas use in Hungary:

Astonishingly, but based on statistical data, the total total methane emissions in 2024 are still more than **12% of the total natural gas consumption in Hungary,** that is, **1,05** billion Nm^3, which is **71%** of the total domestic production!

If the losses so far (about HUF 215 billion lost revenue due to unused methane emissions) **and the expected** CO_{2e} payment obligation (after €30 million burned and/or €556 million leaked methane) are the facts of the [19] **CO_{2e} payment obligation shake up economic decision-makers and system management. There is no need for environmental sensitization, taxes and fines. Simple economic interests make us aware that it is expedient to achieve the goal of ZERO methane emissions and the full conversion of captured methane into energy and materials as soon as possible, not only for the sake of their environmental obligations, but also for their own "pockets". The "GOAL" is to turn the losses into profits! The implementation of the investment required for this takes 4-5 years, and the return on investment is 2-3 years.**

The introduction and maintenance of the best available technical solutions (BAT) on the market as quickly as possible has only resulted in the deterioration of the current situation, with the expansion of energy consumption. New technical solutions need to be developed, validated and brought to the market to achieve the above objective. The introduction and long-term maintenance and expansion of the solutions are motivated by economic interests.

I. *Radical increase in the environmental and energy efficiency of thermal engines (ZE, $NeCO_2$[20].*
II. *Closed-mode flares (with gas soot separation, catalytic on-glow and decarbonization, and flue gas washing (ZE, $NeCO_2$)).*
III. *Complex satellite, air and surface drone LDAR monitoring and AI processing of underground and above-ground pipelines and structures, continuous targeted precision leak elimination with "pipe running and repair robots" (Appendix No. 6) and traditional PPM (planned preventive maintenance) restoration solutions.*
IV. *Retrofit and complete covering of surface structures (pipelines, fittings, compressor stations, natural gas processing plants), from under cover, into which flares, gas engines, gas turbines suck air mixed with possible methane emissions into thermal power engines in accordance with the requirements of Sections I. II.*
V. *Maintaining and continuously transforming the current transmission and storage capacities into a complex sharing network for the collection, storage and distribution of renewable gas sources derived from the gasification of waste and biomass that can be processed in a decentralized manner (approx. 17.6 billion Nm3 available annually in Hungary, which is interchangeable with conventional natural gas and/or LNG in terms of energy and quality, but a) for the collection, storage and distribution of synthesis gas sources resulting from the gasification of waste and biomass.*

In order to prepare for the implementation of the above five points, we will start the elaboration of research and development topic proposals and the search for funding for them.

Budapest, 15.12.2025

Andó Zoltán Tamás

[19] *Burned: (2.88 Mt CO_2) × 40 €/t = ~115 million €. Fugitive (28.7 MB CO_2e) × 40 €/t = ~1.15 billion €. The actual payment obligation depends on the respective legal regime, ETS status, official interpretation and the price applied.*

[20] *Zero emissions (PM, NO_x, TOC, CO, SOx, halogens, etc.) and Negative carbon dioxide emissions by atmospheric carbon capture and utility material conversion.*

Attachments

Annex 1.

Combustion of methane

When 1 kg of methane (CH_4) is burned, the following chemical reaction takes place:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

Calculation process:

Mass of 1 kg of methane in moles:

1. Molar mass of methane (CH_4): 12 + 4×1 = 16 g/mol

1 kg = 1000 g, so 1000 g ÷ 16 g/mol = 62.5 mol methane

Amount of carbon dioxide produced:

Reaction ratio: 1 mol CH_4 → 1 mol CO_2

So, 62.5 moles of methane produce 62.5 moles of carbon dioxide

Carbon dioxide mass:

Molar mass of CO_2: 12 + 2×16 = 44 g/mol

62.5 mol × 44 g/mol = 2750 g = 2.75 kg

When 1 mol of methane is burned, 2 moles of water are produced, and 2 moles of oxygen are required for combustion. When burning 62.5 moles of methane:

Water produced: 62.5 mol × 2 = 125 mol H_2O

Mass of water: 125 mol × 18 g/mol = 2250 g = 2.25 kg

Oxygen required: 62.5 mol × 2 = 125 mol O_2

Mass of oxygen: 125 mol × 32 g/mol = 4000 g = 4.0 kg

Since the air contains about 21% oxygen by volume, the amount of air required is:

4.0 kg of oxygen ÷ 0.21 ≈ 19.05 kg of air- 4.0 kg of pure oxygen can be converted to cubic meters in normal condition (0 °C, 101.325 kPa) with a molar volume of approx. 22.4 liters/mol. Since 125 moles of oxygen are required, this means 125 × 22.4 liters = 2800 liters, i.e. 2.8 normal cubic meters (Nm^3) of oxygen. Similarly, 19.05 kg of air in normal condition corresponds to 19.05 kg ÷ 1.293 kg/m^3 ≈ 14.75 Nm^3 based on the air density (approx. 1.293 kg/m^3).

To determine the volume of the flue gas produced, we need to add up the volume of the gases produced during the reaction (CO_2 and H_2O vapor) and the excess nitrogen not used in the reaction, since 79% of the air is nitrogen, which does not react but becomes part of the flue gas.

CO_2: 62.5 moles of methane produce 62.5 moles of CO_2. This is 62.5 × 22.4 = 1400 Nm^3.

H_2O (vapor): 1 mol of methane produces 2 moles of water, so 62.5 × 2 = 125 moles of H_2O, which is 125 × 22.4 = 2800 Nm^3.

N2: 79% by volume of 14.75 $Nm^3$of air is nitrogen, i.e. 14.75 × 0.79 ≈ 11.65 Nm^3.

The volume of the total flue gas is: 1.4 + 2.8 + 11.65 ≈ **15.85 Nm^3**. That is, the volume of the resulting flue gas will be approximately **15.85 Nm^3** in the normal state.

The calorific value of natural gas is typically **expressed in MJ/kg** or **MJ/m^3**. In Hungary, the calorific value of natural gas per volume is:

Average 34-35 MJ/m^3 the density of natural gas in its normal state:

approx. 0.7–0.8 kg/m^3 Based on this, the calorific value by weight can be calculated:

$$\frac{34\text{ MJ}}{0.7\text{ kg}} \approx 48.6\text{ MJ/kg}\ \mathit{and}\ \frac{35\text{ MJ}}{0.7\text{ kg}} \approx 50\text{ MJ/kg}$$

As described above: when burning 1 kg of natural gas, approx. 49-50 MJ of thermal energy is released.

Annex 2.

IPCC Emission Factors (CO_2, CH_4, N_2O) **for different fuels**
(IGES No. 1*, according to the GHP* ***approach*** *[24]****)***

Some typical IPCC emission factors for different fuels, in kg/TJ. They show how much greenhouse gas is produced when 1 terajoule of energy is produced.

Fuel type	CO_2 (kg/TJ)	CH_4 (kg/TJ)	N_2O (kg/TJ)
Natural gas	**56 100**	**1**	**0.1**
Gasoline	69 300	3	0.6
Diesel	74 100	3	0.6
Charcoal (black)	94 600	1	1.5
Brown coal	96 100	1	1.5
Firewood (wood biomass)	112 000	30	4
LPG (liquefied gas)	**63 100**	**1**	**0.1**

9*. Table: 1996 revised IPCC guidelines for national lists of greenhouse gases: Reference manual [25] and the IPCC Emission Factor Database [26]*

CO_2 values are the highest, as it is the main combustion product. **CH_4 and N_2O** are produced in smaller quantities, but their Global Warming Potential (GWP) is much greater.

Biomass has high CO_2 emissions but is often considered "carbon neutral" if produced sustainably. In the present study, we use the red values first, and the orange values secondly. Gray values are only taken into account.

Example: Natural gas is transported through high-pressure pipelines. During transportation, the pressure gradually decreases due to friction and other losses. To counteract this, compressor stations are installed in the system, which raises the gas pressure again.

These compressors are powered by gas engines or gas turbines. According to the above (**Table** 7), the carbon dioxide equivalent influencing the climate balance determined according to the official IPCC protocol produced as TJ can be determined as follows:

During the operation of gas engines, the following are produced by the combustion of natural gas: Carbon dioxide (CO_2) – the main combustion product. Methane (CH_4) – as a loss during combustion. Dinitrogen oxide (N_2O) – in smaller quantities. The number of emissions depends on: The type of engine (e.g. piston vs. turbine) The quality of the natural gas. From the efficiency of combustion.

The engines use the transported natural gas as fuel, so there is no need for an external source of energy. This means that **the production of 1 TJ of energy from natural gas results in approximately 56 tonnes of CO_2 emissions. The calculation method currently in force does not take into account the CO_2 equivalent of PM, NO_x and TOC emissions.**

Example: I calculate the estimated greenhouse gas emissions of a compressor station that uses 100,000 standard cubic meters (Nm^3) of natural gas per year.

Conversion: $Nm^3 \rightarrow$ TJ

The energy content of natural gas depends on its composition, but according to the IPCC and domestic standards, the average calorific value is:

1 Nm^3 of natural gas ≈ 34–39 MJ (Average: 36 MJ/Nm^3 → 0.000036 TJ/Nm^3)

$$100\,'000\ Nm^3 \times 0.000036\ TJ/Nm^3 = 3.6\ TJ$$

IPCC emission factors for natural gas	Emission factor (kg/TJ)	Estimated emissions (kg)
CO_2	**56 100**	**202 000**
CH_4	**1**	**3.6**
N_2O	**0.1**	**0.36**

Aggregate Emissions:

CO_2: approx. 202 tonnes/year

CH_4: approx. 3.6 kg/year

N_2O: approx. 0.36 kg/year

If we also consider the Global Warming Potential (GWP):

CH_4: 28-30x effect

N_2O: ~265x effect

CO_2 clearly dominates, but CH_4 and N_2O also have a significant climate impact in small amounts.

CO_2 equivalent based on GWP

To calculate the CO_2 equivalent (CO_2e), the mass of each greenhouse gas is multiplied by its global warming potential (GWP). Based on the IPCC's 5th Assessment Report, the following GWP values are used for a 100-year time period: **CO_2:** 1; **CH_4**: 28, **N_2O**: 265

Historical emission values (for 100,000 Nm^3 of natural gas)

Gas Type	Output (kg)	GWP	CO_2-Equivalent (kg)
CO_2	202 000	1	202 000
CH_4	3.6	28	100.8
N_2O	0.36	265	95.4

Cumulative CO_2 equivalent:

$$202\,000 + 100.8 + 95.4 = 202\,196.2\ kg\ CO_2e/Year$$

This means that the **annual CO_2 equivalent emissions of the compressor station are around 202.2 tonnes** if it uses 100,000 Nm^3 of natural gas.

Annex 3.

IPCC Guidelines for the Determination of the Carbon Equivalent of Methane Direct Combustion and Fungunitive CH4GWP100 AR6 (2024) and Expected Quota/Tax
Liability with Approach No. 2 (Official)

Currently, the EU ETS mostly refers to CO_2 emissions rather than methane (CH_4). The CO_2 tax is calculated when combustion occurs, but as stated in *the "EU Methane Regulation 2024",* when it comes to methane emissions, LDAR and other restrictions apply, not taxes. However, if we look at CO2 emissions, let's say at the EU level, the tax rate can be 40 EUR/t CO_2. The global warming potential (GWP100) of CH4 is taken into account when calculating emissions.

Material: natural gas predominantly methane (CH_4); we are approaching a typical Hungarian network composition.

Condition: normal cubic meters (Nm^3) — 1.053 billion Nm^3 of natural gas.

Time horizon for climate impact: GWP100 (IPCC AR6) in accordance with regulatory/reporting practice.

Target: separate number for direct combustion CO_2 and fugitive CH_4 in CO_2 equivalent; and taxation/quota relevance for the listed types of installations.

Specific emission factors:

CH_4 Density (Nm^3): $\rho_{\mathrm{CH_4}} \approx 0.716\ \mathrm{kg/Nm^3}$
Combustion CO_2 (stoichiometric): 1 mol CH_4 → 1 mol CO_2;
Direct CO_2 ≈ per weight (normal state).$1.96\ \mathrm{kg\ CO_2/Nm^3}$
Metán GWP100 (AR6): $\mathrm{GWP}_{100,\mathrm{CH_4}} \approx 27.2$
Specific CO_2e for fugitive methane (without combustion):0.716 kg/Nm^3x27.2≈ $19.5\ \mathrm{kg\ CO_2e/Nm^3}$

Note: With GWP20, the factor is ~82–85, i.e. the CO_2e would be about 3× higher. Most legal/reporting frameworks use GWP100.

Facility groups: technological and reporting aspects:

In the case of extraction, processing, transmission lines, fittings, boosters, the main risks are leakage, ventilation, unplanned emissions (CH_4). Measurement and reporting obligations: LDAR, mass balance, flow measurement, estimation factors; CO_2e report (GWP100). Natural gas processing plants (e.g. Százhalombatta, Tiszaújváros, Kazincbarcika): Main emissions: combustion CO_2 from energy production units + technological CH_4 losses. The combustion emissions are ~1.96 kg CO_2/Nm^3; 19.5 kg CO_2e/Nm^3 is calculated in the summary table. Heat engines, district heating stations: Main emission: combustion CO_2. Efficiency affects energy-based intensity, but m^3-based direct CO_2 specific does not. Calculated with 1.96 kg CO_2/Nm^3 of natural gas consumed. Residential heaters: Main emission: combustion CO_2; fugitive for small-scale but calculable technical audits. What to calculate: 1.96 kg CO_2/Nm^3 for the gas consumed; possible leakage in CO_2e.

Determination of the simple loss cost of methane emissions at 2024 prices:

Natural gas prices in Hungary in 2024 were highly volatile as the European energy market was affected by significant market and geopolitical impacts. For industrial consumers, the wholesale price of natural gas in 2024 averaged around 40-50 euros/MWh, but exchange prices could fluctuate from month to month. Converted to cubic meters (1 Nm^3 ≈ 0.0105 MWh), this meant a price of around EUR 0.42 to 0.53 per Nm^3.

Retail prices may differ as they may be regulated and subsidized. The total loss of 1.054 billion Nm^3 of natural gas sales in Hungary at market prices, the total value of the total volume based on wholesale prices may range from approximately EUR 443 to 559 million (HUF 172 to 217 billion) (EUR 1.054 billion × EUR 0.42 to 0.53 per Nm^3). It should be noted that the specific selling price depends on the terms of the contract, the current stock exchange prices, and the agreement between the buyer and seller.

2024	Methane emission sources in Hungary						
Group Totals	CH_4	Operations Natural Gas Volume Flow	direct combustion (torch, gas engine, gas		TOC content of leakage and ventilation flue gases		Totals
u. of m.		million Nm^3	%	MNm^3	%	MNm^3	MNm^3
1.	**Volumetric flow of natural gas extraction**	**1 486**	*0,25*	**3,7**	*3,55*	**52,8**	**56,5**
	Algyő-Makó (Makó did not produce due to the shutdown of the shale gas project.)	884,2	*0,25*	2,2	*3,6*	31,4	33,6
	Lovászi (no significant extraction)	0,5	*0,25*	0,0013	*3,6*	0,0178	0,0
	Üllés and Forráskút (no significant extraction)	1,2	*0,25*	0,0030	*3,6*	0,0426	0,0
	Endrőd (no significant extraction)	1,3	*0,25*	0,0033	*3,6*	0,0462	0,0
	Pusztaföldvár (supplies depleted)	-	*0,25*	0,0000	*3,6*	0,0000	0,0
	Szank-Kiskunhalas (no significant extraction)	1,2	*0,25*	0,0030	*3,6*	0,0426	0,0
	Hajdúszoboszló (cushion gas extraction)	595,4	*0,25*	1,5	*3,6*	21,1	22,6
	Minor Extractions	2	*0,25*	0,0055	*3,6*	0,0781	0,1
2.	**Volumetric flow of natural gas transmissions and transfers**	**15 866**	*1,6*	**253,9**	*1,7*	**269,7**	**523,6**
	Natural Gas Tarnzite	**6 630**	*1,6*	**106,1**	*1,7*	**112,7**	**218,8**
	Natural gas import volume flow	**7 750**	*1,6*	**124,0**	*1,7*	**131,8**	**255,8**
	Natural gas pressure boosting stations	**15 866**	*2*	**317,3**	*1,2*	**190,4**	**507,7**
	Hajduszoboszló	2 156	*2*	43,1	*1,2*	25,9	69,0
	Mosonmagyaróvár	2 289	*2*	45,8	*1,2*	27,5	73,2
	Gellénháza	2 230	*2*	44,6	*1,2*	26,8	71,4
	Városföld	2 213	*2*	44,3	*1,2*	26,6	70,8
	Csanádpalota	2 041	*2*	40,8	*1,2*	24,5	65,3
	Szada	2 413	*2*	48,3	*1,2*	29,0	77,2
	Báta	2 342	*2*	46,8	*1,2*	28,1	74,9
	Nemesbükk	2 524	*2*	50,5	*1,2*	30,3	80,8
	Conveyor lines (45-70Bar, FGSZ Zrt.)	**15 866**	*1,4*	**222,1**	*1,9*	**301,5**	**523,6**
	Distribution lines (1-4 bar, E.ON, MVM Égáz-Dégáz, OPUS, TIGÁZ)	**2 558**	*0,05*	**1,3**	*3,15*	**80,6**	**81,8**
	Private pipelines (20-30mBar, estimated figure: 3.9 million gas receivers 45-100ekm)	**2 558**	*0,01*	**0,3**	*3,2*	**81,6**	**81,8**
3.	**The volume flow of the natural gas reservoir**	**4 430**	*0,8*	**35,4**	*2,1*	**93,0**	**128,5**
	Pusztaderics	340	*0,8*	2,7	*2,1*	7,1	9,9
	Hajduszoboszló	1 640	*0,8*	13,1	*2,1*	34,4	47,6
	Zsana	2 170	*0,8*	17,4	*2,1*	45,6	62,9
	Kardoskút	280	*0,8*	2,2	*2,1*	5,9	8,1
4.	**Methane emissions from natural gas processing**	**2 558**	*0,8*	**20,5**	*2,8*	**71,6**	**92,1**
	Danube oil refinery (Százhalombatta)	500	*0,8*	4,0	*2,1*	10,5	14,5
	Tisza Chemical Plant (Tiszaújváros)	550	*0,8*	4,4	*2,1*	11,6	16,0
	BorsodCHEM (Kazincbarcika)	350	*0,8*	2,8	*2,1*	7,4	10,2
5.	**Volumetric flow of distribution to natural gas receivers**	**8 525**	*0,8*	**68,2**	*2,1*	**179,0**	**247,2**
	Distribution lines	2 558	*0,05*	1,3	*3,15*	80,6	81,8
	Private pipelines	767	*0,01*	0,1	*3,2*	24,5	24,6
6.	**Natural gas use**	**8 525**	*2,8*	**238,7**	*1,2*	**102,3**	**341,0**
	Private users	2 558	*0,01*	0,3	*3,2*	81,6	81,8
	Support combustion of power plants, waste incinerators, negligators	200	*0,01*	0,0	*3,2*	6,4	6,4
	Other large industrial consumers (e.g. glass factories, power plants, fertilizer factories)	200	*0,01*	0,0	*3,2*	6,4	6,4
Total:				***381,7***		***672,5***	***1054,2***

10. Table: Hungary's natural gas extraction, transportation, storage, processing and consumption methane emissions taking into account normal volume flows weighted by operation and grouped by consumption.

Methane emissions and reduction options for natural gas extraction, transportation, storage, distribution and use

2024	Methane emission sources in Hungary		Climate Impact CO_2 Equivalent Million Tonnes					
Group Totals	CH_4	Totals	Direct combustion CO_2	Expected quota/tax liability	FUGNITIVE CH_4GWP100 IPCC AR6	Expected quota/tax liability	Total CO_2 equivalent	Expected quota/tax liability
u. of m.		MNm^3	Mega tonna	million €	Mega tonna	million €	Mega tonna	milion €
1.	**Volumetric flow of natural gas extraction**	**56,5**	0,01	**0,3**	1,03	**41,1**	1,04	**41,4**
	Algyő-Makó (Makó did not produce due to the shutdown of the shale gas project.)	33,6	0,00	0,2	0,61	24,5	0,62	24,7
	Lovászi (no significant extraction)	0,0	0,0000	0,0001	0,0003	0,0138	0,000	0,014
	Üllés and Forráskút (no significant extraction)	0,0	0,0000	0,0002	0,0008	0,0332	0,001	0,033
	Endrőd (no significant extraction)	0,0	0,0000	0,0003	0,0009	0,0360	0,001	0,036
	Pusztaföldvár (supplies depleted)	0,0	-	-	-	-	-	-
	Szank-Kiskunhalas (no significant extraction)	0,0	0,0000	0,0002	0,0008	0,0332	0,001	0,033
	Hajdúszoboszló (cushion gas extraction)	22,6	0,0029	0,1167	0,4122	16,4866	0,42	16,6
	Minor Extractions	0,1	0,0000	0,0004	0,0015	0,0609	0,00	0,1
2.	**Volumetric flow of natural gas transmissions and transfers**	**523,6**	0,50	**19,9**	5,26	**210,4**	5,76	**230,3**
	Natural Gas Tarnzite	**218,8**	0,21	8,3	2,20	87,9	2,41	96,2
	Natural gas import volume flow	**255,8**	0,24	9,7	2,57	102,8	2,81	112,5
	Natural gas pressure boosting stations	**507,7**	0,62	**24,9**	3,71	**148,5**	4,33	**173,4**
	Hajduszoboszló	69,0	0,08	**3,4**	0,50	**20,2**	0,59	**23,6**
	Mosonmagyaróvár	73,2	0,09	**3,6**	0,54	**21,4**	0,63	**25,0**
	Gellénháza	71,4	0,09	**3,5**	0,52	**20,9**	0,61	**24,4**
	Városföld	70,8	0,09	**3,5**	0,52	**20,7**	0,60	**24,2**
	Csanádpalota	65,3	0,08	**3,2**	0,48	**19,1**	0,56	**22,3**
	Szada	77,2	0,09	**3,8**	0,56	**22,6**	0,66	**26,4**
	Báta	74,9	0,09	**3,7**	0,55	**21,9**	0,64	**25,6**
	Nemesbükk	80,8	0,10	**4,0**	0,59	**23,6**	0,69	**27,6**
	Conveyor lines (45-70Bar, FGSZ Zrt.)	**523,6**	0,44	**17,4**	5,88	**235,1**	6,31	**252,5**
	Distribution lines (1-4 bar, E.ON, MVM Égáz-Dégáz, OPUS, TIGÁZ)	**81,8**	0,00	0,1	1,57	62,8	1,57	62,9
	Private pipelines (20-30mBar, estimated figure: 3.9 million gas receivers 45-100ekm)	**81,8**	0,00	0,0	1,59	63,6	1,59	63,7
3.	**The volume flow of the natural gas reservoir**	**128,5**	0,07	**2,8**	1,81	**72,6**	1,88	**75,3**
	Pusztaderics	9,9	0,01	0,2	0,14	5,6	0,14	5,8
	Hajduszoboszló	47,6	0,03	1,0	0,67	26,9	0,70	27,9
	Zsana	62,9	0,03	1,4	0,89	35,5	0,92	36,9
	Kardoskút	8,1	0,00	0,2	0,11	4,6	0,12	4,8
4.	**Methane emissions from natural gas processing**	**92,1**	0,04	**1,6**	1,40	**55,9**	1,44	**57,5**
	Danube oil refinery (Százhalombatta)	14,5	0,01	0,3	0,20	8,2	0,21	8,5
	Tisza Chemical Plant (Tiszaújváros)	16,0	0,01	0,3	0,23	9,0	0,23	9,4
	BorsodCHEM (Kazincbarcika)	10,2	0,01	0,2	0,14	5,7	0,15	6,0
5.	**Volumetric flow of distribution to natural gas receivers**	**247,2**	0,13	**5,3**	3,49	**139,6**	3,62	**145,0**
	Distribution lines	81,8	0,00	0,1	1,57	62,8	1,57	62,9
	Private pipelines	24,6	0,00	0,0	0,48	19,1	0,48	19,1
6.	**Natural gas use**	**341,0**	0,47	**18,7**	1,99	**79,8**	2,46	**98,5**
	Private users	81,8	0,00	0,0	1,59	63,6	1,59	63,7
	Support combustion of power plants, waste incinerators, negligators	6,4	0,00	0,0	0,12	5,0	0,12	5,0
	Other large industrial consumers (e.g. glass factories, power plants, fertilizer factories)	6,4	0,00	0,0	0,12	5,0	0,12	5,0
Total:		***1054,2***	*0,75*	***29,9***	*13,11*	***524,6***	*13,86*	***554,49***

11. Table: Hungary's natural gas extraction, transportation, storage, processing and use, methane emissions directly and the weather-influencing effect taken into account according to the fugitive IPCC AR6 (2024), expressed in carbon dioxide equivalent. CO_2 equivalent modeling of the indirect impact of methane on the climate over a 20-year period is approximately 3x times higher than the values projected over 100 years.

Annex 5.

Extract from the study "NON-CO_2 EMISSIONS FROM STATIONARY COMBUSTION" [27]

"In parallel with the CO_2 emissions caused by stationary combustion, five main non-CO_2 greenhouse gases are released during the combustion process: CH_4, N_2O, NO_x, CO and NMVOCs (TOC). In addition, due to the sulfur content of fossil fuels, a significant amount of SO_2 is released during combustion, which can affect the climate, although SO_2 is not a greenhouse gas. All these gases are addressed in *the revised 1996 IPCC Guidelines for National Lists of Greenhouse Gases* (*IPCC Guidelines*).

The technical approach to estimating CO_2 emissions is relatively simple, and the level of accuracy is high, as CO_2 emission factors are mainly a function of the properties of the fuel, which are generally well managed by most countries. However, non-CO_2 emissions are closely linked to a number of parameters specific to each combustion plant: the type of technology, the combustion process; operating and maintenance conditions, size and year of combustion equipment, emission control policy, fuel characteristics, etc. ... ... the different greenhouse gases covered by the IPCC guidelines:

CH_4

CH4 is released in limited quantities due to the incomplete combustion of hydrocarbons from the combustion of fuels. Methane emissions depend on the temperature of the boilers[21] and depends. In large combustion plants and industrial applications, emission rates are very low, while in smaller applications such as residential applications (e.g. small stoves, open combustion) they are much higher. The contribution of stationary combustion to total CH4 emissions is generally low, with uncertainty medium to high. Therefore, according to the IPCC guidelines, the application of the simplified Level 1 approach consists of an aggregate fuel/source allocation. However, it may be necessary to pay more attention to a methodological approach to biomass use, given that biomass combustion contributes significantly to CH4 emissions in countries with high biomass consumption, especially in developing countries.

N_2O

~~N_2O comes directly from the combustion of fuel[22]. The emission of N_2O depends on the temperature of the boilers. Emission rates are highest when the combustion temperature ranges from 800 °C to 1200 °C, while emissions are negligible below 800 °C and above 1200 °C.~~ The mechanisms of N_2O chemistry are relatively well understood, although experimental data are limited. As with CH_4, the contribution of stationary combustion to total N_2O emissions is small, and uncertainty is high. In addition, reliable emission factors are not yet available for all sources. Therefore, the IPCC guidelines allow for a very simplified Level 1 approach, which takes into account the allocation of aggregate fuel/source. Estimates of N_2O emissions from biomass use are poorly documented and emission factors are uncertain.

NO_x

Nitrogen oxides (NO_x) are indirect greenhouse gases. Fuel combustion activities are the most significant anthropogenic sources of NO_x, with the energy industry and mobile sources being the

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[21] *and also depends on the excess air...*

[22] *In 30 years of thermal power plant measurement experience, we have not experienced N_2O emissions. Nitrous oxide (nitrous oxide, nitro) is formed during the degradation and decomposition of biological materials. N_2O is combustible. During the combustion of natural gas, the nitrogen content of the air sucked into the heat engine oxidizes above 1000 °C and its degree also depends on the pressure of the combustion chamber. (E.g.: the auto-ignition of diesel engines takes place at a pressure of 200 - 250 Bar. In this case, a large amount of nitric oxide is produced suddenly, for a short period of time. Diesel engines have extremely high untreated NO_x emissions.) 99.6 – 99.996 % of the flue gases (1250-2480 ppm NO and 1-5 ppm NO_2) emanating untreated from heat engines, but in the atmosphere, they are completely converted into nitrogen dioxide under the influence of light.*

most important. Two different NO_x formation mechanisms can be distinguished. "NO" is the formation of fuel from the conversion of chemically bound nitrogen in the fuel, and "thermal NO" is formed by the participation of atmospheric nitrogen during the combustion process. ~~Most of the NO_x emitted from coal (80-90%) is formed from fuel nitrogen~~[23]. Excess air and high temperatures, depending on the type of boiler and the process operations, encourage the formation of NO_x. The IPCC guidelines express NO_x emissions ($NO+NO_2$) from the combustion of fossil fuels on a full molecular basis, assuming that all NO_x emissions are emitted as NO_2.

In the case of petroleum and natural gas, less than 50% of the NO_x emitted is generated from fuel nitrogen, while the total amount of NO_x emitted from gas is generated from thermal nitrogen. The estimated NO_x emission factors should be adjusted according to the emission reductions applied in the country.

IPCC guidelines prescribe certain default reduction efficiencies for coal-fired installations if information on these installations is not available in the country.

CO

Carbon monoxide (CO) is an indirect greenhouse gas. While automobiles are the most significant fuel burner of CO, small residential combustion plants are also important.
The process of CO formation is directly influenced by usage patterns, the type and size of the technology, its vintage, maintenance and operation. It should be noted that emission rates can vary by several orders of magnitude and are particularly affected by operating and maintenance conditions, especially for older or smaller equipment.

Small wood stove appliances, which are widely used in the developing world, have a particularly high emission potential (and vary depending on the region and conditions of use) due to inefficient combustion.

Overall, stationary combustion generally contributes to a small but still significant portion of national CO emissions.

NMVOCs

Non-methane volatile organic compounds (NMVOCs) are indirect greenhouse gases. NMVOCs are the result of incomplete combustion and are directly influenced by usage patterns, type and size of technology, vintage, maintenance, and how the technology works.

It should be noted that emission rates can vary by several orders of magnitude depending on operating and maintenance conditions, especially for older or smaller equipment. Emissions are usually very low for larger combustion plants, where the combustion process is more efficient.

While mobile sources are the most significant fuel source for NMVOCs, small residential combustion plants, especially those that use biomass, are also important.

Small wood stove appliances, which are widely used in the developing world, have a particularly high emission potential (and vary by region and conditions of use) due to inefficient combustion appliances.

However, the most accurate statement **of non-CO_2 emissions from stationary combustion** would be to have all the necessary data on the specific emission factors (EF) and activity data (AD) of each combustion plant in a given country.

The tables below are helpful in interpreting the IPCC's guidelines for particulate PM emissions below 10 microns in this study have not yet been worked out. It then came into the spotlight in

[23] *Purified natural gas has a negligible, but even mine gas has a very low nitrogen content. This statement is primarily valid for biomass and wood combustion. Even in the case of low-temperature gasification of them, NOx emissions are negligible (0-3 ppm).*

2015 (after the diesel scandal). When using the tables below, we also take into account the influencing capabilities of PM climate. We are convinced that N_2O is not emitted from heat engines, only NO, which is completely oxidized to NO_2 under the influence of light.

Emission types/factors	Default emission factor (kg/TJ input timber)	Default emission factor (kg/TJ produced charcoal)
CH_4	**300**	**1000**
~~N_2O~~	~~N/A~~	~~N/A~~[24]
NO_x	**5**	**10**
CO	**2000**	**7000**
NMVOC-k (**TOC**)	**600**	**1700**
(**PM)**	**556**	**1442**
Forrás: 1-14. táblázat – 3. kötet – IPCC iránymutatások, 1996.		

12. Table: Default non-CO_2 emission factors for charcoal production (Kg/TJ)

For informational purposes, we present the other tables of the study, which were considered during the compilation of the simulation developed in our study.

Sources of issue		Coal	Natural gas	Oil	Wood/Wood waste	Charcoal	Other biomass and wastes
Other biomass and wastesEnergiaipar (fogyasztásból eredő kibocsátás)		**1**	**1**	**3**	**30**	**200**	**30**
Energy industry (emissions from charcoal production)	kg CH_4/TJ Wood Input				300		
	kg CH_4/TJ Wood Inputszén kimenet					1000	
Feldolgozóipar és építőipar		10	5	2	30	200	30
More Sectors	Commercial/Institutional	10	5	10	300	200	300
	Residential	300	5	10	300	200	300
	Stationary agriculture/ forestry/ fisheries	300	5	10	300	200	300

13. Table: Energy industry non-CO_2 emission factors (kg/TJ)

Sources of issue		Szén	Coal	Oil	Wood /Wood waste	Charcoal	Other biomass and wastes
Energiaipar (fogyasztásból eredő kibocsátás)		**1.4**	**0.1**	**0.6**	**4**	**4**	**4**
Energy industry	kg N_2O /TJ Wood input	**-**	**-**	**-**	**-**	**-**	**-**

[24] *The N_2O di-nitrogen monoxide "nitro" is a powerful fuel for combustion. The Internal combustion engines are often used to increase short power by increasing engine power by 20-30% for short time by injection through the intake system. Nitrogen monoxide is released from the heat engines, which is converted into nitrogen dioxide in a short time.*

Sources of issue		Szén	Coal	Oil	Wood /Wood waste	Charcoal	Other biomass and wastes
(emissions from charcoal production)	kg N_2O /TJ Carbon performance	-	-	-	-	-	-
Manufacturing and construction		1.4	0.1	0.6	4	4	4
More	Commercial/Institutional	1.4	0.1	0.6	4	1	4
Sectors	Residential	1.4	0.1	0.6	4	1	4
	Stationary agriculture/forestry/fisheries	1.4	0.1	0.6	4	1	4

14. Table: N_2O Default (uncontrolled) emission factors (kg/TJ)

Sources of issue		Coal	Natural gas	Oil	Wood / Wood waste	Charcoal	Other biomass and wastes
Energy industry (emissions from consumption)		**300**	**150**	**200**	**100**	**100**	**100**
Energy industry (emissions from charcoal production)	kg NO_x /TJ Wood input				5		
	kg NO_x /TJ Carbon performance					10	
Manufacturing and construction		100	150	200	100	100	100
More	Commercial /Institutional	100	50	100	100	100	100
Sectors	Residential	100	50	100	100	100	100
	Stationary agriculture/forestry /fisheries	100	50	100	100	100	100

15. Table: NO_X Default (uncontrolled) emission factors (kg/TJ)

Sources of issue		Coal	Natural gas	Oil	Wood /Wood waste	Charcoal	Other biomass and wastes
Energy industry (emissions from consumption)		**20**	**20**	**15**	**1000**	**1000**	**1000**
Energy industry (emissions from charcoal production)	kg CO /TJ Wood Input				2000		
	kg CO /TJ Carbon performance					7000	
Manufacturing and construction		150	30	10	2000	4000	4000

Sources of issue		Coal	Natural gas	Oil	Wood /Wood waste	Charcoal	Other biomass and wastes
Más	Commercial/ Institutional	2000	50	20	5000	7000	5000
Sectors	Lakossági	2000	50	20	5000	7000	5000
	Stationary agriculture/ forestry /fishing	2000	50	20	5000	7000	5000

*16. Table: **CO** Default (uncontrolled) emission factors (kg/TJ)*

Sources of issue		Coal	Natural gas	Oil	Wood /Wood waste	Charcoal	Other biomass and wastes
Energy industry (emissions from consumption)		**5**	**5**	**5**	**50**	**100**	**50**
Energy industry (emissions from charcoal production)	kg NMVOC/TJ fabevitel				600		
	kg NMVOCs/TJ szénteljesítmény					1700	
Manufacturing and construction		20	5	5	50	100	50
More Sectors	Commercial/Institutional	200	5	5	600	100	600
	Residential	200	5	5	600	100	600
	Stationary agriculture/forestry/fisheries	200	5	5	600	100	600
Source: 1996 IPCC Guidelines, Volume 2.							

*17. Table: NMVOCs **(TOC)** Default (uncontrolled) emission factors (kg/TJ)"*

Consideration of PM, NO_x, TOC and SO_2 for the indirect effects of ozone O_3 (Approach 3: CO_2 modelling for 20 to 100 years**)**

According to the latest (NO_x cycle) modeling algorithm description, NO is lighter than air and according to the image, NO_2 promotes ozone formation in the troposphere and ozone depletion in the stratosphere as a catalyst. TOC (Total Organic Carbon) or VOCs also contribute to ozone formation.

O_3 ozone NO_x and TOC promote ozone formation, which is a greenhouse gas in the troposphere. estimated GHG: **~ 2'000 – 4'000** (over a 20-year time horizon), but **only for modelling purposes** These values **are not used in official CO_2 equivalent calculations** as ozone is **a secondary pollutant** and cannot be directly accounted for as emissions

TOC (Total Organic Carbon) or VOCs also contribute to ozone formation.
It can form SO_2 aerosols, which have a cooling effect but are not considered GHG.

The IPCC and the GHG protocol do not take these into account in the calculation of CO_2-equivalent emissions, except in specific modelling cases. It can form SO_2 aerosols, which have a cooling effect but are not considered GHG. The IPCC and the GHG protocol **do not take these into account in the calculation of CO_2-equivalent emissions**, except in specific modelling cases.

The following special simulation spreadsheet takes into account the indirect impact of natural gas extraction, transportation, processing, storage and distribution, as well as the emission of harmful substances from heat power plants in use.

IN >	NATURAL GAS consumption million Nm^3	GAS ENGINES mega tons CO_2 emissions (current regulations)	GAS TURBINES mega tons CO_2 emissions (current regulations)	TORCHES mega tons of CO_2 emissions (current regulations)	THERMAL ENGINE mega tons of CO_2 emissions (real measurement)	KMH X CO_2 equivalent	OUT >
	8525	12,5	7,9	12,3	22,1	CO_2	
Limits	PM (ngramm/nm^3)	0	4	5	35	1445	Factors
	NO (mgramm/nm^3)	190	150	250	452	451	
	TOC (mgramm/nm^3)	55	0	0	78	84	
	CO (mgramm/nm^3)	245	100	100	130	2	
	SO_2 (mgramm/nm^3)	0	0	35	65	35	

18. Table: Carbon dioxide equivalents of the harmful substances released during the processing and use of natural gas that affect indirect weather

The factors elaborated in the table do not calculate from the power output of the heat engine, because in practice there is no statistical data for that. The input of the spreadsheet calculated is based on the natural gas consumption collected per unit of the heat engine for a period of time, e.g. for a year (e.g.: 8'525 million Nm^3). Harmful substances are also released from the power part of the natural gas burned in thermal power plants, which are expelled as losses with the flue gas when unused, so if, according to the IPCC guidelines, the indirect and direct weather-influencing effect of flue gases from useful work (kg/TJ) were to be summarized on the basis of time-weighted power output, then its practical analysis would mean a very high theoretical uncertainty and a lot of administrative work. Therefore, in the present study, we determined the indirect and direct effect of the operation of thermal power engines as a function of the volume flow (Nm^3) of the fuel consumed, in this case natural gas. In principle and in practice, simulation uncertainty due to the different efficiency of different thermal engines can be ruled out.

Conclusions: in order to determine the carbon dioxide equivalent calculated directly from methane combustion, in accordance with the reporting obligation according to the IPCC recommendations, multiply the normal state natural gas volume flow (Nm^3) **by a factor of "0.00196"** and the result of the product gives the carbon dioxide produced in tonnes. Based on 2024 statistical data, the cumulative auxiliary energy demand related to natural gas supply increased by losses, 381.7 million Nm^3 of natural gas volume flow was released, and 748'132 tons of carbon dioxide was released from methane burned in flares, boilers, gas engines and gas turbines. Of the 5'967 million Nm^3 of natural gas used in thermal power plants operating in Hungary, 11.7 million tons of carbon dioxide was released.

To determine the fugitive leaking or non-combustion vented methane carbon dioxide equivalent, multiply the normal natural gas volume flow (Nm^3) by **a factor of "0.0195"** and the product gives the weather-influencing effect of methane in tonnes. The indirect fugitive carbon dioxide emission equivalent of 672.5 million Nm^3 related to natural gas supply is 11.69532 million tonnes. The indirect and direct effects are almost the same.

From the methane used in thermal power plants operated in Hungary, we recorded a state of natural gas consumption in Hungary (Table 18). for example, of the use of gas engines, gas turbines, flares and boilers. The table assumes in the first approach that the given thermal power unit complies with the regulations in force. In the second approach, we simulated the indirect weather-influencing effect of the gas engine's harmful emissions by entering the real measurement data of a thermal power engine (2.4 MW gas generator) expressed in 22,1 million tons of carbon dioxide.

Annex 6.

Pipe-In Walking, Repair Robots

Are there robotic systems under development that are capable of detecting leaks and performing certain repairs while moving inside high-pressure natural gas pipelines?

Yes, there are robotic systems under development that are capable of detecting leaks and performing certain repairs while moving inside high-pressure natural gas pipelines. These are commonly referred to as "in-pipe robots" or "pipe running robots" and are designed to inspect and repair pipes from the inside rather than costly and risky earthworks. *Are there robotic systems under development that are capable of detecting leaks and performing certain repairs while moving inside high-pressure natural gas pipelines?*

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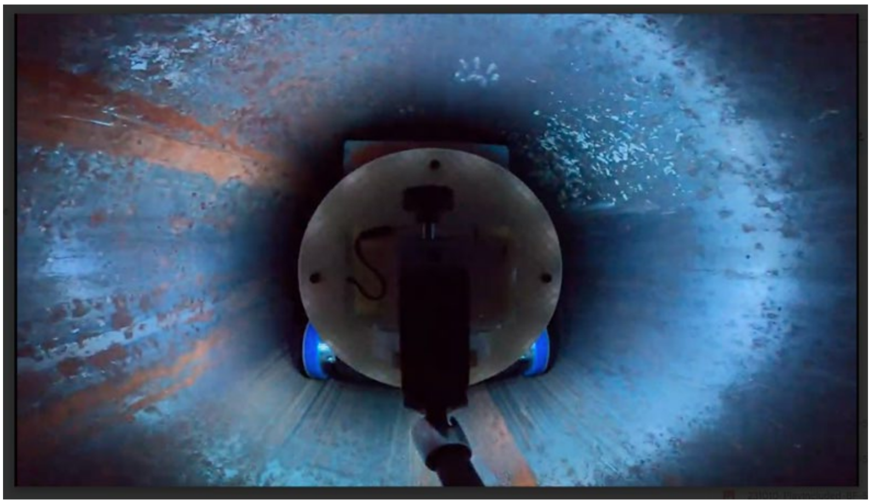

How do these systems work?

- Modular robots: For example, researchers at Carnegie Mellon University (CMU) have developed a robot that can map wires, detect leaks, and apply a resin coating to the inner wall of CMU School of Computer Science by rolling inside a pipe.
- REPAIR program (ARPA-E, DOE): Supported by the U.S. Department of Energy, the program aims to resurface existing, aging steel and cast iron lines from the inside to avoid a complete replacement at CMU School of Computer Science.
- Smart pipes and in-pipe robots: Other research sites (e.g., MIT Mechatronics Lab) are working on systems that continuously monitor the condition of the pipe, collect data, and repair mechatronics.mit.edu if necessary.

Benefits

- Cost reduction: Traditional earthmoving repairs can cost up to $10 million per mile; internal robotic repairs can cost a fraction of that , according to CMU School of Computer Science.

Safety: Robots reduce workers' exposure in hazardous environments.

- **Long-term solution**: The goal is for the repairs to **be durable for at least 50 years,** according to CMU School of Computer Science.

Limitations and current status

- These systems are still mainly in the research and experimental phase, and their industrial scale, their routine use is limited.
- So far, robots have shown results mainly in smaller-diameter distribution lines; in the case of high-pressure, large-diameter conveyor lines, the technology is more complicated.
- At present, the repair capability is limited to coating and minor defect management, not to the replacement of a complete pipe section.

Sources: CMU School of Computer Science mechatronics.mit.edu

In-pipe robots that detect and repair leaks inside high-pressure natural gas transmission pipelines *are currently not* widely used in Hungary. In the domestic high-pressure network operated by FGSZ Ltd. and MGT Ltd., maintenance and inspection are mainly carried out using traditional methods (external corrosion protection, cathodic protection, remote monitoring, pressure and flow monitoring) mindentafoldgazrol.hu FGSZ.

Situation in Hungary

- FGSZ Ltd. It operates the nearly 5'889 km long high-pressure natural gas transmission system, with a diameter of 80–1'400 mm and an operating pressure of 40–75 bar mindentafoldgazrol.hu FGSZ .

- The wires are externally coated and equipped with an active cathodic protection system, which is monitored by a remote monitoring system. This ensures that the pipes do not puncture and that faults are detected in time FGSZ.

- Leak detection is currently based **on external monitoring and measuring points**, not internal robots.

International developments

- Pilot programs are running in the USA and Western Europe (e.g. **ARPA-E REPAIR program**), which are designed to have **robots inspect and repair wires from the inside**.
- These systems **are still in the research phase** and have been tested mainly in smaller diameter distribution lines.

- The technology has not yet been introduced in the industry of high-pressure, large-diameter conveyor lines.

Why is this technology not yet in application in Hungary?

- **Technology maturity**: Robots are currently not suitable for routine use in industrial-scale, high-pressure systems.
- **Cost and regulation**: In the Hungarian system, cathode protection and external monitoring are already proven, regulated methods.
- **Safety Requirements**: Robotic repairs in high-pressure lines would pose serious licensing and safety challenges.

The following EU research projects are currently underway for the internal robotic inspection and repair of gas pipelines, and how can they fit into the Hungarian system?

There are currently several EU research projects aimed at the internal robotic examination and repair of pipelines, but they have not yet been applied in industry in Hungary.

- **TUBERS (Horizon Europe, 2022–2026)**
  - Goal: to develop scalable and modular robot platforms that are able to continuously monitor and repair faults inside the pipelines.
  - Solutions:
    - A "snake-like" robot for long-distance movement and networking.
    - Soft robots for repairing pipe sections.
    - High-precision leak and corrosion detection system.
    - An AI-based decision support system for locating errors and selecting repair strategies.
  - Funding: €3.14 million total cost, of which €2.4 million is EU funding CORDIS.
- **PIPEON (Robotics and AI for Sewer Pipe Inspection and Maintenance, 2024–2028)**
  - Led by: Tallinn University of Technology (TalTech).
  - Goal: to develop autonomous robots that are able to use the sewer network to:
    - carry out a health check,
    - install sensors,
    - blockages.
  - Budget: €8 million, with 12 partners (e.g. University of Sheffield, NTNU, European technology companies).
  - Expected result: testing of prototypes in several European networks watereurope.eu by the 2030s.

EPRG (European Pipeline Research Group)

  - It is not a specific robot project, but a consortium of researchers dealing with the integrity of oil and gas pipelines.
  - Role: Evaluation of standards, testing methods, and new technologies that can be directly related to robotic testing EPRG.

Hungarian relevance

- In Hungary, FGSZ Ltd. and MGT Ltd. It relies on traditional corrosion protection and remote monitoring.
- The results of the EU projects are expected to appear in domestic practice in the medium term (around 2030), especially in the case of aging steel pipelines.

- The projects running within the framework of Horizon Europe are in line with the EU's climate and air quality goals, so they can also be integrated into the Hungarian legislation.
- The EU Methane Strategy (2020) states that reducing methane leaks in the energy sector is key to achieving the 2030 climate targets.

The EU Methane Regulation (2024) provides

- mandatory leak and repair programs (LDARs),
- regular monitoring and reporting.
- quick repair of leaks.
- The goal: a 30% reduction in methane emissions in the energy sector by 2030.

Connectivity of robotics projects

- TUBERS and PIPEON type in-pipe robots are capable of:
  - real-time leak detection,
  - repair on site,
  - data collection and digital reporting.
- This directly supports the EU LDAR regulations, as robots can ensure compliance in an automated and continuous manner.

- The data collected by robots can be integrated into orts under the EU ETS (Emission Trading System) and the GHG Protocol.

Typical diameter ranges

- Smaller diameters (around 200-300 mm)
  - Many developments are targeted at water, gas, and oil distribution lines with an inner diameter of 8 to 10 inches (≈200 to 250 mm).
  - Example: Development of Pune University of Technology that can move in pipes 8 to 10 inches in diameter, even scmrglobal.org on elbows and T-shapes.
- Medium diameters (300-600 mm)
  - Here, adaptive, wall-pressed robots are already in operation, which are able to adjust to different diameters.
  - According to the developments published by IEEE, these robots can be adjusted in a wide range, making them suitable for testing mixed networks IEEE Xplore.
- Large diameters (900-1200 mm)
  - There are robots specially developed for high-pressure water and gas pipes, which can move up to 1.2 meters in inner diameter.

  - Example: the development of the Korea Institute of Robotics, which operates in pipes with a diameter of 900 to 1200 mm, equipped with a camera, LiDAR and magnetic flux leak detector MDPI.

Important Note:

- In high-pressure transmission lines (e.g. 80–1400 mm diameter in Hungary), the industrial application of robots is still limited.

- Such robots have already been successfully tested in smaller-diameter distribution lines, but the technology is still in the experimental phase in large-diameter, high-pressure systems.

- The size and operating range of the robots are always determined by the inner diameter of the pipe and the pressure conditions.
- In-pipe robots are most often able to move in pipes with a diameter of 200-1200 mm. smaller models are suitable for distribution networks (≈200-300 mm), while larger, complex systems can operate up to 1.2 meters in diameter. Routine application in high-pressure conveyor lines is still under development.

Repairable errors with robots

- Micro leaks
  - Detection: gas detection sensors, acoustic microphones, pressure change detectors.
  - Fix: applying an inner resin coating or polymer layer that seals the pores.
  - Application: has already been successfully demonstrated in distribution lines.
- Corrosion stains, thinning of the inner wall
  - Detection: magnetic flux leakage (MFL), ultrasonic examination.
  - Repair: coating renovation (epoxy, polymer) that restores the integrity of the wall.
  - Effect: longer lifespan, reduced methane loss.
- Minor cracks, hairline cracks
  - Detection: high-definition camera + ultrasound.
  - Repair: an internal coating that mechanically seals the crack.
  - Note: it is only effective if the crack does not spread further.

Defects where robots are limited

- Large cracks or fractures
  - Robots are currently unable to perform mechanical ppipereplacements.
  - In this case, external earthworks and welding are required.
- Complex fitting failures (e.g. flanges, valves)
  - Robots are not capable of replacing or repairing fittings.
  - These will still need to be treated manually.
- High-pressure, large-diameter conveyor lines
  - The operation of robots is still in the experimental phase here.
  - Due to the pressure and diameter, coating application and repair are technically more complicated.
- In pipe robots are primarily suitable for handling micro leaks, corrosion defects and minor cracks, while major structural defects and assembly problems still require conventional repairs. Technology currently works well in distribution lines, and the application in high-pressure transmission lines is still in the research phase.

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