Master theses

Hydrogen generation at gas distribution stations

Egor Ovchinnikov

03/07/2023

Chair of Mining Engineering and Mineral Economics
Department Mineral Resources Engineering
Montanuniversitaet Leoben

A-8700 LEOBEN, Franz Josef Straße 18
Phone: +43 3842-402-2001
Fax: +43 3842-402-2002
bergbau@unileoben.ac.at

Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Abstract

Currently, the world has taken a trend towards decarbonization and hydrogen energy is considered as one of the main ways to achieve carbon neutrality. According to some estimates, by 2050 hydrogen share in the energy balance could increase significantly.

As interest in hydrogen energy has arisen relatively recently, there are no ready-made solutions for the hydrogen production at gas distribution stations. In nature, hydrogen practically does not occur in its pure form and is extracted from other compounds using chemical reactions. Therefore, for the hydrogen production on an industrial scale, it is necessary to search for additional energy capacities. One of these sources is the energy of gas lost during reduction at gas distribution stations.

Long-distance gas transfer requires high pressure, which has to be reduced before the gas is conveyed to the customers. This pressure reduction takes place at natural gas pressure reduction stations, where gas pressure is decreased by using gas flow energy for overcoming local resistance, represented by a throttling valve. This pressure energy can be reused, but it is difficult to implement it at small pressure reduction stations, as the values of unsteadiness significantly increase when the gas approaches consumers, whereas gas flow rate and pressure decrease. This work suggests installation of expander-generator units, based on volumetric expanders, at small pressure reduction stations. An experiment was conducted to study gas-dynamic processes, which take place in expander-generator units. The system showed stable operation in non-stationary conditions and the feasibility of using an expander-generator regulator as a primary one for a small natural gas pressure reduction station was confirmed.

Purpose of the work – development of a concept for the production of "green" hydrogen on the basis of a gas distribution station using the energy of gas pressure.

Zusammenfassung

Derzeit gibt es weltweit einen Trend zur Dekarbonisierung und Wasserstoffenergie gilt als einer der wichtigsten Wege zur Erreichung der CO_2-Neutralität. Einigen Schätzungen zufolge könnte der Anteil von Wasserstoff an der Energiebilanz bis 2050 deutlich steigen.

Da das Interesse an Wasserstoffenergie erst seit relativ kurzer Zeit besteht, gibt es noch keine fertigen Lösungen für die Wasserstoffproduktion an Gasverteilerstationen. Wasserstoff kommt in der Natur praktisch nicht in reiner Form vor und wird durch chemische Reaktionen aus anderen Verbindungen gewonnen. Für die Wasserstoffproduktion im industriellen Maßstab ist daher die Suche nach zusätzlichen Energiekapazitäten erforderlich. Eine dieser Quellen ist die Gasenergie, die bei der Reduktion an Gasverteilungsstationen verloren geht.

Der Gastransport über weite Distanzen erfordert einen hohen Druck, der vor der Weiterleitung des Gases an den Kunden reduziert werden muss. Diese Druckreduzierung findet an Erdgas-Druckreduzierungsstationen statt, wo der Gasdruck durch Nutzung der Gasströmungsenergie zur Überwindung lokaler Widerstände, dargestellt durch ein Drosselventil, gesenkt wird. Diese Druckenergie kann wiederverwendet werden, ist jedoch bei kleinen Druckreduzierungsstationen nur schwer umsetzbar, da die Werte der Instabilität bei der Annäherung des Gases an die Verbraucher deutlich ansteigen, während die Gasdurchflussmenge und der Gasdruck sinken. Diese Arbeit schlägt die Installation von Expander-Generator-Einheiten auf Basis volumetrischer Expander an kleinen Druckreduzierstationen vor. Es wurde ein Experiment durchgeführt, um gasdynamische Prozesse zu untersuchen, die in Expander-Generator-Einheiten ablaufen. Das System zeigte einen stabilen Betrieb unter instationären Bedingungen und die Machbarkeit der Verwendung eines Expander-Generator-Reglers als Primärregler für eine kleine Erdgas-Druckreduzierungsstation wurde bestätigt.

Zweck der Arbeit – Entwicklung eines Konzepts zur Herstellung von „grünem“ Wasserstoff auf Basis einer Gasverteilerstation unter Nutzung der Energie des Gasdrucks.

Table of Contents

1 Introduction

The gas transmission network of Russia is extensive, it includes many compressor stations, gas distribution points, electrochemical protection installations, etc. There are more than 300,000 GDSs alone, of which only 4,000 are large gas distribution stations. The main purpose of the gas distribution point is to reduce the gas pressure, from the pressure at which it is transported over long distances (up to 20 MPa) to the pressure values of gas-using equipment (2-600 kPa) and maintain it at this level. To reduce energy losses during gas transportation, the flow pressure is reduced step by step along the entire delivery chain to the consumer. Therefore, the reduction of gas pressure is fundamental part of the transportation mechanism and it is not possible to exclude it. Accordingly, finding new ways of reduction with conservation of gas pressure energy is topical.

Pressure energy losses in traditional pressure regulators occur due to the mechanism of the regulator operation: the pressure decreases due to the dissipation of the energy of the pumped gas to overcome local resistance. Additionally, pressure regulators based on a throttle valve have certain disadvantages, for example: low accuracy, small operating range, lack of remote control, short service life of the sensing element.

Obviously, using the pressure energy flow to rotate the expander will make it possible to use energy for various needs.

The paper considers the technology of recuperation of previously lost pressure energy with the help of turbo-expanders. The resulting energy is proposed to be used for the production of hydrogen at the gas distribution station.

2 Process design

2.1 Gas pressure reduction at gas distribution points

Natural gas supply networks are extensive; there are branched systems that include gas distribution points, cathodic protection installations, etc. The gas transmission system of Russia includes at least 90,000 electrochemical protection units (ECP) and more than 300,000 gas reduction points (GRP), of which only 4,000 are large gas distribution stations (Joint Stock Company Gazprom Gas Distribution 2023). Gas reduction points are designed to reduce the high pressure at which gas is transported (up to 20 MPa) to a consumer level of 2-600 kPa (Kostowski/Usón 2013). The pressure decreases in stages as it approaches the consumer, which reduces energy costs for transportation. Therefore, reduction is a standard operation in gas transportation and it is not possible to transport gas without it. Therefore, the reduction technology itself and the energy losses associated with it in the gas flow are of the greatest interest.

The operation of the reduction point is determined by the following parameters: gas pressure and temperature at the inlet and outlet of the reduction point, gas flow rate and ambient temperature.

Consideration should be given to the dependence of the gas temperature at the inlet to the gas distribution point on the ambient temperature.

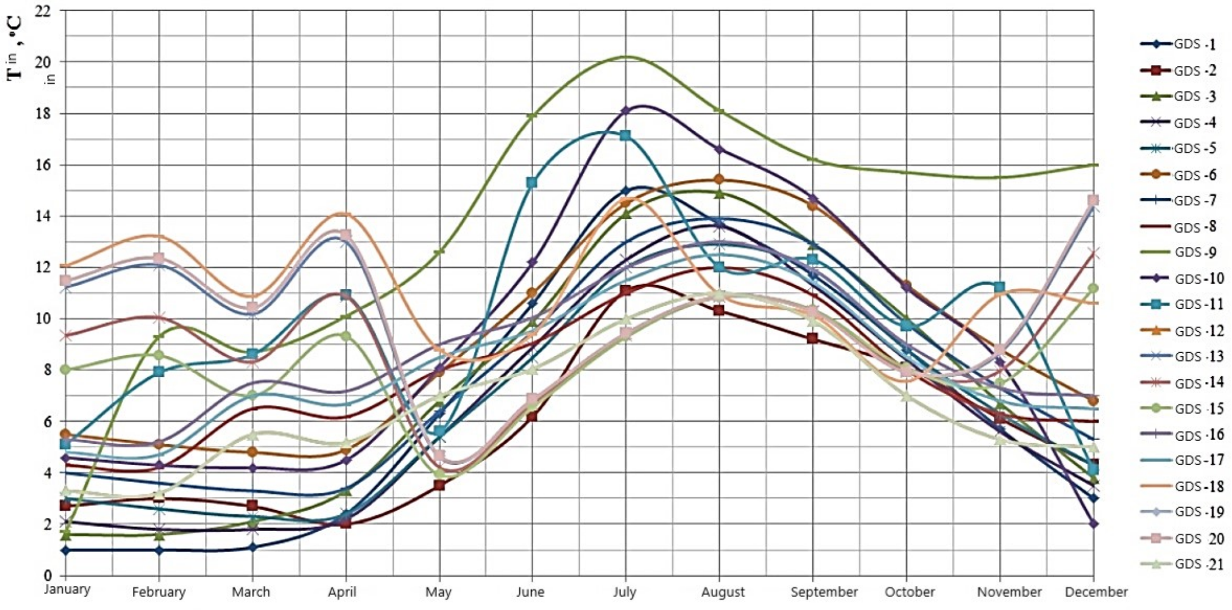


Figure 1: **Fluctuations in gas temperature at the inlet to the gas distribution point during the year (Gataullina et al. 2013)**

GOST 5542-2014 introduces requirements for the gas temperature at the outlet of the reduction point, which must be maintained above the dew point. This value, depending on the pressure, temperature and humidity of the pumped gas, is in the range from -7℃ to -12℃.

GOST 5542-2014 introduces requirements (GOST 5541-2014 2014) for the gas temperature at the outlet of the reduction point, which must be maintained above the dew point. This value, depending on the pressure, temperature and humidity of the pumped gas, is in the range from -7℃ to -12℃ (Garanin et al. 2012).

End-user gas consumption varies by season, day of the week and hour of the day (Golyanov 2008).

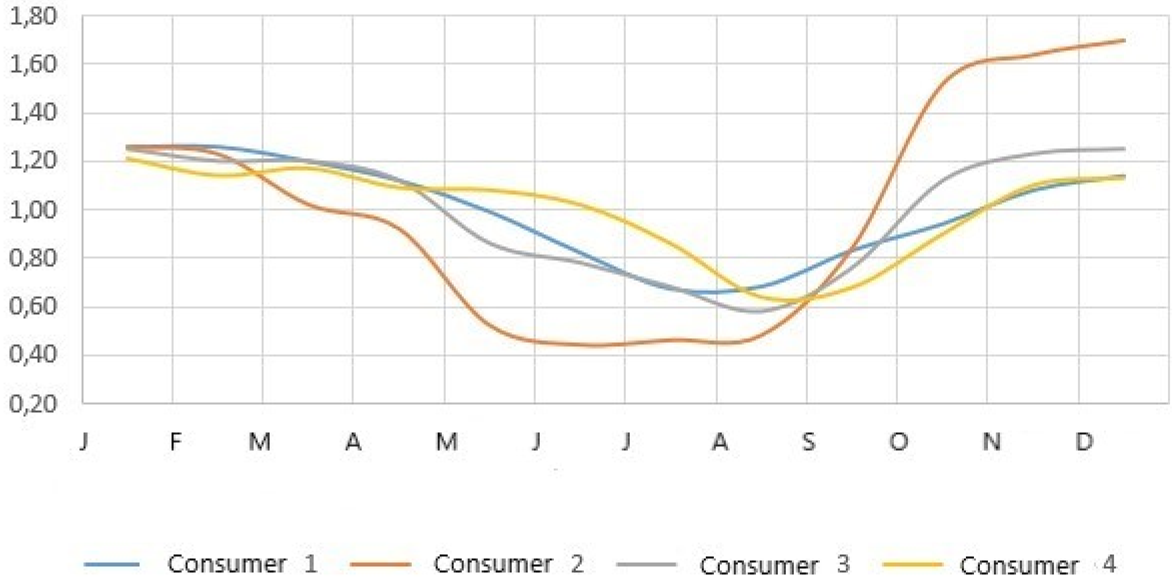


Figure 2: **Coefficient of monthly unsteadiness (Arshinov 2012; Suslov 2015)**

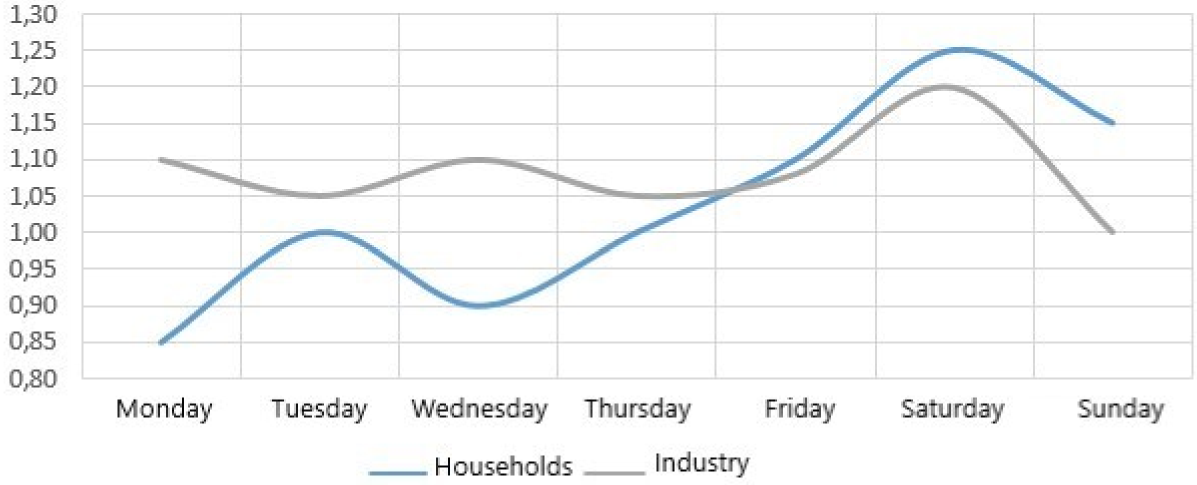


Figure 3: **Coefficient of daily unsteadiness (Arshinov 2012; Suslov 2015)**

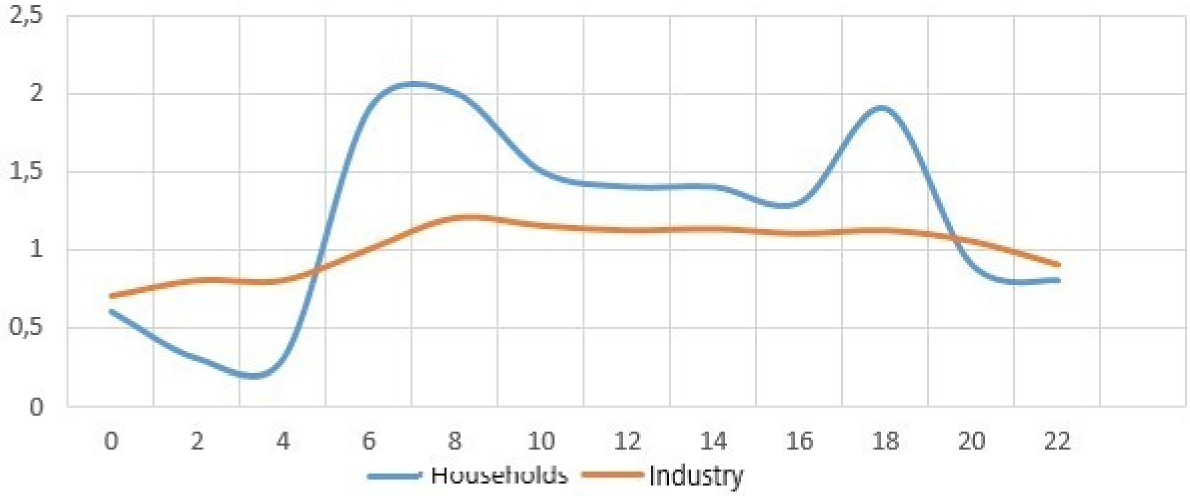


Figure 4: **Coefficient of hourly unsteadiness (Arshinov 2012; Suslov 2015)**

On average, during the year the ratio of the maximum level of gas consumption to the minimum can reach 2.3-2.6 times, during the week the consumption can change up to 1.1-1.2 times, during the day this indicator can change by 1, 6-2.2 times.

The main pressure losses at GRP are associated with the pressure reduction mechanism by using gas pressure energy to overcome local resistance in the form of a pressure regulator (PR) throttle valve (Kargaran et al. 2013). Also, the traditional pressure regulator has certain disadvantages, such as: low accuracy, relatively small operating range, lack of remote control and short life of the sensing element (Sheikhnejad et al. 2020).

It is obvious that the energy recovery of the pressure of the gas flow at the expander will make it possible to direct this energy to useful work (Kostowski 2010). A similar option was proposed by Millionshchikov back in 1947. Expander units can perform various tasks at reduction points, such as: power generation, gas liquefaction (He/Ju 2013), cogeneration (Badami et al. 2017; Farzaneh-Gord et al. 2007; Farzaneh-Gord/Sadi 2008; Leusheva/Morenov 2017), etc.

Often, the installation of expansion machines at large gas distribution stations is economically and energetically justified (Badami et al. 2017; Danieli et al. 2020; Rahman 2010). The biggest part of turboexpanders today range from 1 to 12 MW and operate at consistently high flow rates and pressure drops.

In the USSR, expanders have been installed since 1985 at compressor stations and large gas distribution stations, and in Russia since 1994 at the Ryazan and Sredneuralskaya state district power stations, at CHPP-21 and CHPP-23. Modern developments and prototypes of high-power expander-generators in Russia are possessed by:

- OOO "Turboden", Moscow;
- ZAO "Cryokor-Energy", Moscow.

Compared to steam and gas turbine plants, high power turboexpanders show a lower unit cost of installed power, higher energy efficiency, since up to 60% of gas is saved per 1.0 kW of power, the flow path also has a higher efficiency in the range from 70% to 80%. Additionally, turboexpanders have a short payback period (2.5-5 years) and do not produce polluting emissions into the atmosphere.

But there are also disadvantages in the form of the need for additional heating of the gas due to cooling by up to 45-70 ° C; operation at flow rates from 20,000 Nm^3/h and above; high operating costs and the need to stabilize the frequency of electricity produced in conditions of non-stationary gas flow.

The above features allow expander-generator units to operate efficiently in fields at high gas temperatures, when gas cooling during expansion acts as one of the stages of low-temperature separation, or at thermal power plants, where gas flow is stable and there is a lot of cheap heat for heating it.

The above features allow expander-generator units to operate efficiently in fields (Zarnitsky 1968) at high gas temperatures, when gas cooling during expansion acts as one of the stages of low-temperature separation, or at thermal power plants, where gas flow is stable and there is a lot of cheap heat for heating it (Stepanets 1999).

Today, to power the power-consuming devices of gas distribution stations, turbo-expanders with a power of up to 50 kW are being developed, as the most appropriate, however, there are practically no examples of their widespread use (Fokin G.A. 2015).

The disadvantages of turbo-expanders with a power of up to 50 kW are due to the sensitivity to the presence of condensate in the composition of the pumped gas; complex and expensive design; high rate of rotation and the need to maintain high pressure and stabilize the gas flow through the expander.

In the conditions of small reduction points at pressures up to 0.3 MPa and powers up to 1.5 kW, expander-generator units based on volumetric expansion machines can become an alternative to turbine machines, since they are devoid of their disadvantages (Karasevich et al. 2016).

Today, expanders with a power of up to 50 kW are the most suitable devices for generating energy at reduction points. At the same time, as it approaches the end consumers, the flow rate and pressure of the pumped gas flow decrease, and the unsteadiness increases. As a result, there are voltage surges in the power supply network of the expander-generator and unstable operation of the turbines (Hossain et al. 2011; Mohod/Aware 2010), as well as the economic inexpediency of introducing the installation and inefficient energy consumption (Taheri Seresht et al.

2010). Most small gas distribution stations with flow rates up to 500 m^3/h and pressure drops up to 6 atmospheres are affected by unstable flow rates and pressures (Taleshian et al. 2012). Under these conditions, turboexpanders must be operated at higher speeds, which leads to a more complex design and a reduction in overhaul intervals and, as a result, to economic inexpediency.

In addition, it is necessary to take into account the significant cooling of the gas from expansion during the passage of the expander. Burner gas heaters (Rastegar et al. 2020), are traditionally used to restore its temperature, and various secondary energy resources, such as renewable (Arabkoohsar et al. 2016, 2015; Schipachev/Dmitrieva 2021) and low-potential energy sources (Barbarelli et al. 2018; Borelli et al. 2018; Farzaneh-Gord et al. 2016; Xiong et al. 2018), are widely considered promising.

Despite the low attractiveness of individual small GRPs for pressure energy recovery, due to distribution over large areas, the total energy intensity of the gas transmission system is very high. The own needs of the station and electrochemical protection installations in electricity for stable operation can be covered by expander generators. Thanks to this, it will be possible to reduce or abandon power consumption from third-party sources (power lines) and, accordingly, reduce the cost of connecting to them. It will also reduce the level of manual labor through automation, which will ultimately improve the efficiency and environmental friendliness of the gas transportation and distribution system.

STO Gazprom 2-6.2-1028-2015 („Gazprom“, Russian joint-stock company 2017) for gas distribution points with a gas flow rate of less than 50 m^3/h establishes requirements for power supply in the amount of one independent power source (power line, battery, etc.), which is determined as the main one. The task of the power supply source is a reliable supply of electricity, depending on the category of the supplied object. Basically, the 3rd reliability category is applied to the objects of the gas transmission system, which allows a break in the external power supply for up to 24 hours (Fokin G.A. 2015).

The main consumption of electricity at gas distribution facilities is provided by telemetry and mechanics systems, communication centers and metering, security and fire alarms, emergency ventilation and lighting.

The power of cathodic protection stations is determined by the resistance of the soil, the length of the protected area of the soil, and other factors. Today, installations with a capacity of 0.1-3.0 kW are widely used.

Cabinet reduction points consume from 15 to 500 W. Most of the time the system is inactive, so the average power is assumed to be about 15 W.

Large gas distribution stations on average consume no more than 20 kW of power. The maximum consumption is observed during the maintenance work of the equipment due to the need for lighting, this happens for several hours every 2-3 weeks. The rest of the time, the volume of energy consumption falls.

Due to the fact that power lines do not always run close to gas distribution networks, connecting reduction points to them can be time-consuming and costly.

Even with a lower efficiency of pressure energy recovery compared to the efficiency of power plants, an autonomous power supply system for gas distribution facilities will increase the energy efficiency of the system. The question is only in the amount of capital and operating costs.

Considering all of the above, the solution to this problem can be a combination of the functions of a pressure regulator and a disposal unit in the form of an expander-generator unit (EGU) based on a volumetric expander. In addition to the fact that today there are practically no reduction and disposal systems for small gas distribution points, the novelty of this solution is, firstly, in the use of an expansion machine directly as part of the pressure regulator, and not on a separate line, which makes it possible to work with large fluctuations of the flow rate and pressure and significantly reduce the size of the system. Secondly, in the installation of volumetric expanders, which increase the reliability of the system due to ease of maintenance and the absence of the need for high-speed rotation at low flow rates and pressure drops (Diao et al. 2018).

There are various automatic control systems for expander-generator units (Aksenov, D.T., Aksenova, G.P. 2009; Panarin, M.V. et al. 2016), which are based on the principles of flow separation and switching.

A frequently used scheme is an expander installed in parallel with a reduction unit (Neseli et al. 2015; Pozivil 2004). This option implies the use of EGR in conditions of small non-stationarity of gas consumption by consumers. The presence of a traditional pressure regulator means that all the shortcomings of the PR remain.

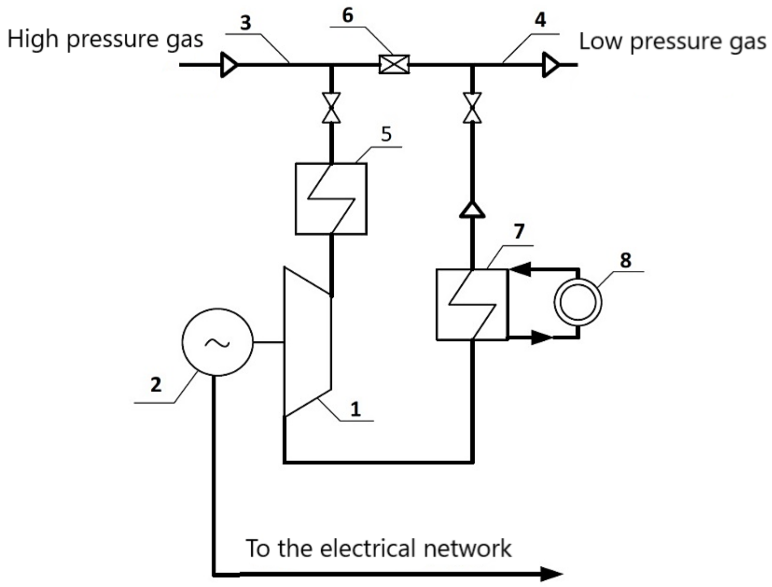


Figure 5: Parallel connection of the expander-generator

1 – expander; 2 – generator; 3 – high pressure pipeline; 4 – low pressure pipeline; 5 – heat exchanger; 6 – gas reduction unit; 7 – heat exchanger; 8 – cold consumer

Another scheme is an EGR connected in series with a traditional pressure regulator. With this connection option, the negative effect of low temperature on the regulator is reduced. But this deprives the design of the possibility of mechanical control of the speed of the expander rotor in conditions of large unsteadiness of gas extraction by consumers (Turbodetanders 2023).

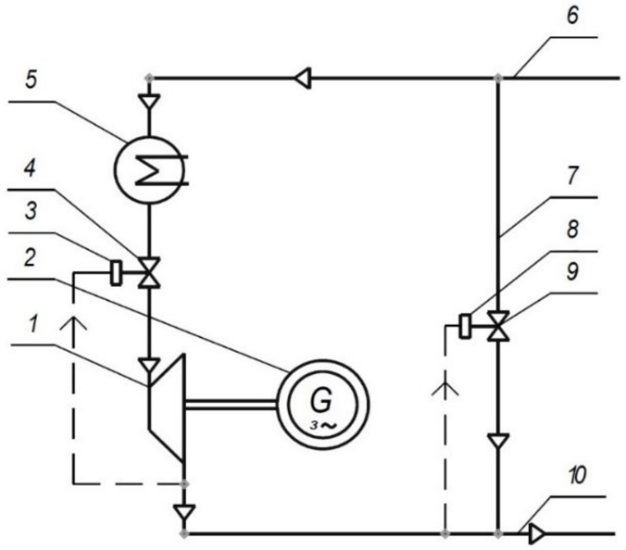


Figure 6: Sequential connection of the expander-generator

1 – turbine; 2 – electric generator; 3 – pressure regulator; 4 – control valve; 5 – gas heater; 6 – high pressure gas pipeline; 7 – bypass pipeline; 8 – pressure regulator; 9 – bypass valve; 10 – low pressure gas pipeline

The most interesting are schemes that make it possible to use an expander to regulate pressure (Xiong et al. 2018). It is possible to regulate the pressure at the outlet of the expander by changing its rotation speed by adjusting the moment of resistance of the generator. In this case, it is possible to exclude throttling valves from the technological scheme of the installation. The analysis of analogue systems and the need to maintain power quality give reason to believe that the cost of the system will be high (Zamyatin et al. 2019).

2.2 Possibility of hydrogen production at GDS

The main consumption of electricity at gas distribution points is provided by instrumentation and automation, electrochemical protection installations, pumps for water heating systems and lighting. Basically, the total power of the systems does not exceed 20 kW.

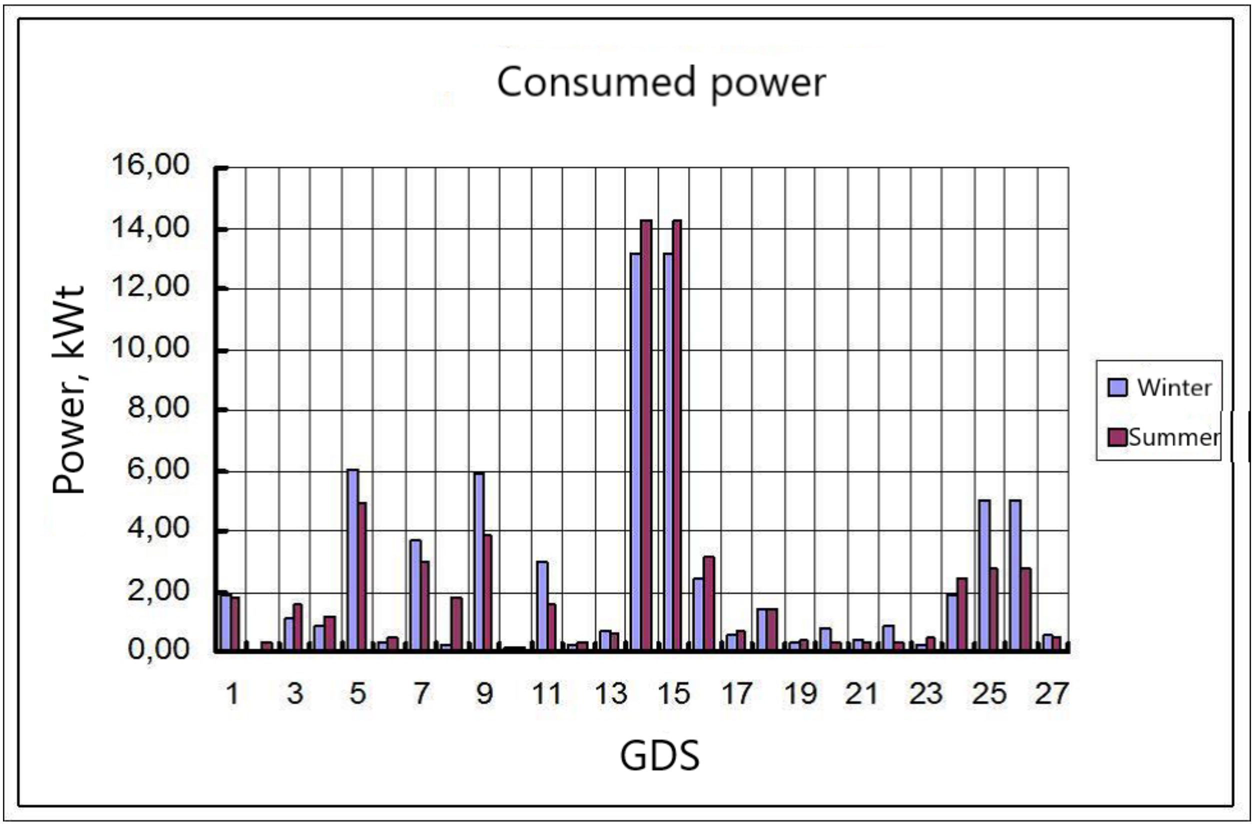


Figure 7: **Energy consumption of various gas distribution stations in the Leningrad region (Fokin G.A. 2015)**

To assess the capabilities of the gas distribution station in terms of generating electricity, the calculation of the potentially obtained capacities of turboexpanders when they are installed at gas reduction points was carried out. Data on the loading of the gas distribution station in the Leningrad region were used as initial values. Several stations were selected for the calculation.

The available power, theoretically generated during the isenthalpy expansion of gas in the turboexpander, is calculated by the formulas (Arshinov 2012; Suslov 2015):

$$\begin{cases} N_{theor} = \mathrm{Cp}_g \cdot G_g \cdot (T_0 - T_2); \\ T_0 - T_2 = T_0 \cdot \left(1 - \frac{T_2}{T_0}\right) = T_0 \cdot \left(1 - \left(\frac{P_2}{P_0}\right)^{\frac{kg-1}{kg}}\right) \\ G_g = Q_g \cdot \rho_g; \end{cases} \quad (1)$$

Using transformations, we derive the general formula:

$$N_{theor} = \mathrm{Cp}_g \cdot Q_g \cdot \rho_g \cdot T_{in} \cdot \left(1 - \left(\frac{P_{out}}{P_{in}}\right)^{\frac{kg-1}{kg}}\right) \quad (2)$$

To assess the real power value, it is necessary to take into account the efficiency of the electric generator, turbine wheel and electric converter:

$$N_r = N_{theor} \cdot \eta_t \cdot \eta_{gen} \cdot \eta_{conv} \quad (3)$$

Initial data: $\mathrm{Cp}_g = 2217 \frac{J}{kg\cdot К}; \rho_g = 0{,}731 \frac{kg}{m^3}; k_g = 1{,}2967; \eta_t = 0{,}6; \eta_{gen} = 0{,}9; \eta_{conv} = 0{,}9.$

№	Name	P_{in_av}	P_{out_av}	T_{in_av}	T_{out_av}	Q_{av}	P_{in}/P_{out}	N_e	P_{in_av}
		kgf/cm^2	kgf/cm^2	C	C	m^3/h		kWt	kgf/cm^2
1	Vostochnaya	33,1	3,6	6	-9,2	24167	9,19	1217,75	591,83
2	Vostochnaya 2	32,7	9,2	6	-6,6	477941	3,55	15321,79	7446,39
3	Zarya	46,2	3,3	6	2,2	772	14	44,14	21,45
4	Zelenogorsk	39,7	3,6	6	12,5	3580	11,03	183,64	89,25
5	Konnaya lakhta	42,8	8,5	6	4,6	191390	5,04	7463,20	3627,12

6	Korobitsyno	45,9	3,5	6	5,5	3095	13,11	176,88	85,96
7	Osinovaya rosha	36,5	1,7	6	3,1	6015	21,47	388,86	188,99
8	Romanovka	33,9	3,6	6	5,6	24765	8,69	1204,60	585,44
9	Severnaya	33,5	9,1	6	6,1	311436	3,68	10103,05	4910,08
10	Sertolovo	35,5	4,2	6	11,5	13289	8,45	654,70	318,18
11	S-Z TEC	47,6	24,8	6	8,7	107390	1,92	1843,55	895,96

Table 1: Power values

As can be seen from the table, it is possible to install expanders with a capacity of about 3-7 MW at 27% of the stations, 45% can provide energy generation in the amount of 100-900 kW, and the remaining 28% of the stations can potentially provide up to 100 kW of power and are not of great interest for expander-generator installations. Calculated data show that stations suitable for EGR installation produce significantly more energy than is required to cover the station's own needs (20 kW) and more than 80 kW of power remain unloaded. This energy can be stored in the form of hydrogen.

2.3 Hydrogen production methods

There are 3 main technologies for hydrogen production: water electrolysis (“green” hydrogen), autothermal or steam reforming of methane (“grey” hydrogen), methane pyrolysis (“blue” hydrogen).

"Green" hydrogen is considered the most promising option in the future, despite the high energy intensity and high cost of the process. "Grey" hydrogen is by far the most developed technology and, accordingly, cheaper than electrolysis. However, there is a disadvantage in the form of carbon dioxide emissions, which requires additional costs for organizing CO_2 capture and storage systems. When generating hydrogen from methane in the absence of oxygen (“blue” hydrogen), no CO_2 emissions into the atmosphere occur and the technology is considered clean.

For installation at a gas distribution station, it is proposed to use the "green" hydrogen technology, since this approach will make it possible to utilize the excess electricity remaining after the gas pressure energy recovery at the expander-generator regulator

2.4 Technological scheme of the electrolysis plant

Electrolysis is preceded by a stage of water preparation. For the operation of the electrolyzer, demineralized (deionized) water is required, that is, water purified from chemical and mechanical contaminants. Since demineralized water is practically non-conductive, alkali is added, mainly potassium hydroxide (KOH), as the most effective option, sodium hydroxide (NaOH) is also used. As a result, after the preparation stage, a 30% KOH solution enters the electrolyzer.

The energy necessary for the splitting of water into hydrogen and oxygen comes from the expander-generator regulator. The mechanical work of the expander is converted into electricity by an asynchronous alternator. The alternating current is then converted into the direct current required by the electrolyzer at the rectifier.

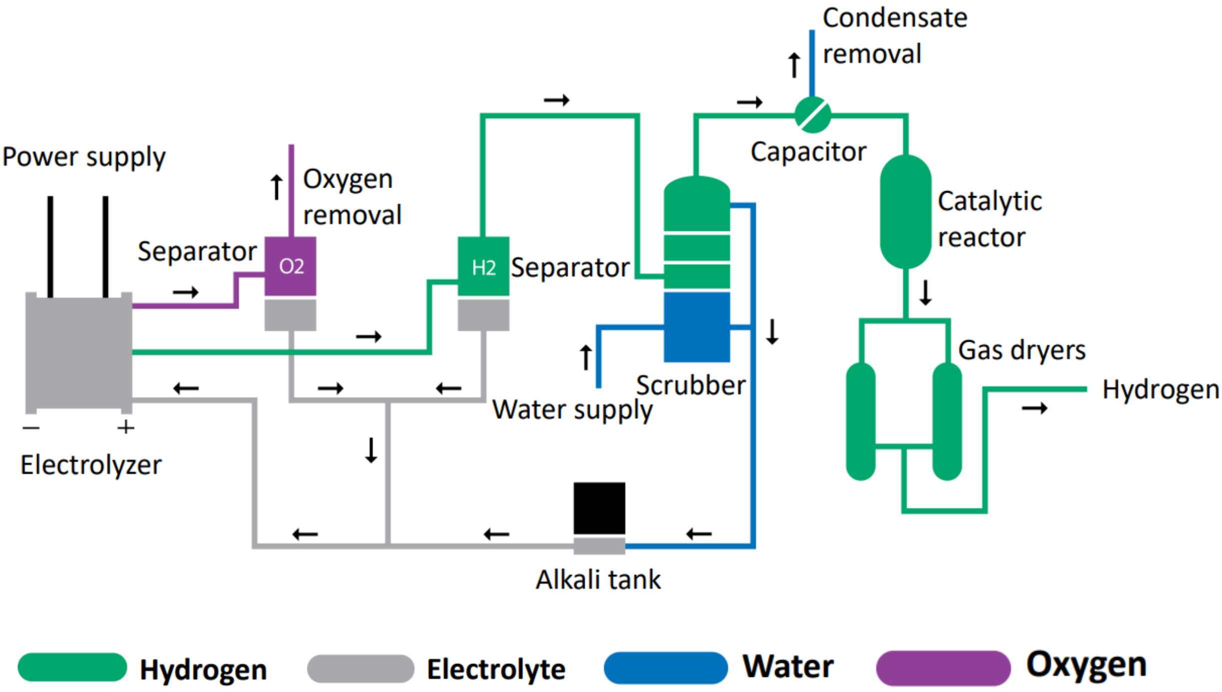


Figure 8: Schematic diagram of the electrolyzer

In the electrolyzer, under the influence of direct current, water splits into oxygen and hydrogen. Further, the gases are removed from the electrolyzer through their own paths, which are completely identical, therefore, the operation of the system is disclosed using the example of a path for hydrogen.

At the first stage, the electrolyte is separated from hydrogen gas. To do this, the mixture is fed to a gas-liquid separator. Hydrogen bubbles are released from the mixture supplied to the bottom of the vessel and go further along the tract. The electrolyte remaining at the bottom is taken back into the electrolyzer.

After passing through the separator, alkali impurities still remain in hydrogen. To separate these impurities, hydrogen enters the scrubber. Deionized water flows through the top of the vessel, and hydrogen gas flows through the bottom. Water, falling down, washes the oncoming gas flow from alkali. The remaining water in the hydrogen is retained by a coalescent filter at the outlet of the scrubber. Water droplets condense on this filter and flow down. After passing through this stage, hydrogen is almost completely purified from alkali impurities.

At this point, the gas has a temperature of about 50°C and is saturated with water vapor. The condenser helps get rid of it. The condenser is a heat exchanger where hydrogen reduces its temperature with the help of a coolant. Condensed water droplets are removed from the system. The oxygen content in the mixture after these purification steps is 0.1-0.5%, and the dew point is at +3°C. In the oxygen path, if this gas is not required by the consumer, at this step it is removed from the system.

The final purification from oxygen takes place in the catalytic purification reactor. Granules of noble metals (platinum, palladium) accelerate the reactions of oxygen with hydrogen to produce water. At the outlet, the percentage of oxygen in the mixture is reduced to 0.0001-0.0005%.

In the final stage, the hydrogen passes through the dryer. Its action is based on the mechanism of short-cycle adsorption. Two adsorber vessels with a special adsorbent dry the mixture, taking water from it. The vessels work alternately while one vessel operates, the second regenerates. After passing through all stages of purification, hydrogen is obtained with an oxygen content of 0.0001% -0.0005% and a dew point of -75 ° C, which can already be sent to the consumer.

2.5 Hydrogen storage

Hydrogen allows to store large amounts of energy for quite a long time and also transport this energy over long distances. This could make hydrogen one of the foundations of a future sustainable global energy system. Therefore, the rational construction of distribution networks will be of fundamental importance.

At present, the main volumes of hydrogen are usually stored in tanks in a gaseous or liquid state. But future large global hydrogen distribution networks will need more hydrogen storage technologies to keep the system running smoothly. For example, a large-scale underground hydrogen storage facility is not required to briefly store hydrogen at an export terminal before shipping it further down the chain. Vehicle refueling stations may need to store hydrogen for several hours, and storing hydrogen for several days or weeks will avoid situations of mismatch between supply and demand. Much longer term and larger storage options will be required if hydrogen is to be used to overcome severe seasonal fluctuations in electricity supply or heat demand or to ensure system resilience. The choice of the most appropriate method depends on the volume, hydrogen injection/pumping rate, geography and storage time. In general, it can be said that for the purpose of short-term storage of small volumes of hydrogen, reservoirs suit better, while for the need to store large volumes for a long time, geological formations are more suitable.

Depleted natural gas or oil reservoirs, aquifers and salt caverns are optimal options for storing large volumes of hydrogen for extended periods of time. They are already being used as natural gas storage facilities and show low operating costs and significant economies of scale. These characteristics mean they are likely to be the cheapest hydrogen storage option, even though hydrogen has a low energy density compared to natural gas (LIU et al. 2017).

The cost of hydrogen storage equipment based on salt caverns in terms of the volume of stored hydrogen is less than 0.6 USD/kg H_2, the active volume of the storage reaches 98% of the total. Also this type of storage has a low risk of contamination of stored hydrogen (Anna S. Lord et al. 2014). The high storage pressure results in a high release rate of the stored gas, making them attractive for industrial and energy applications. Since salt caverns are usually a series of individual adjacent caverns, natural gas storage can be converted to hydrogen storage as usage increases, reducing initial costs.

Depleted oil and gas reservoirs are usually larger in volume than salt caverns, but they are also more permeable and have contaminants that must be removed from pumped hydrogen before it can be used further. Aquifers, on the other hand, have not yet been sufficiently studied, and their suitability for hydrogen storage has not yet been definitively confirmed. As with oil and gas reservoirs, natural barriers trap much of the hydrogen deep underground. However, reactions with microorganisms, liquids and rocks can lead to gas losses. The feasibility and cost of storing hydrogen in depleted oil and gas reservoirs and aquifers remains to be explored. If their suitability is determined, the volume of stored hydrogen will be enough to cover seasonal fluctuations in energy consumption, especially in places a salt caverns are not available.

Thus, hydrogen storage in geological formations appears to be the best option for long-term and large-scale hydrogen storage, but geographical distribution and large size make them less suitable for short-term, small-scale storage applications. For these purposes, tank storage is the most promising option.

Compressed or liquefied hydrogen storage tanks have a high filling rate and gas losses of less than 1% during storage, making them suitable for situations where a local supply of fuel or raw materials is required.

At a pressure of 70 MPa, the energy density of compressed hydrogen is 15% of that of gasoline; accordingly, a volume of hydrogen equivalent in energy value will take up about 6.5 times more space. Ammonia has a higher energy density, which solves this problem. However, the conversion of hydrogen into ammonia and the subsequent reverse transformation require additional energy costs. On the other hand, in terms of vehicles, lithium-ion batteries with similar volumes can store less energy than compressed hydrogen tanks, which means that hydrogen can provide a greater range.

Further studies of reservoir volumes are underway, which will expand the area of their application. Underground reservoirs are being studied for storing compressed hydrogen at pressures greater than 800 bar, what will increase the amount of stored energy. At the initial stage of research, there is the issue of storing hydrogen in solid materials, such as chemical hydrides, which will allow storing hydrogen of even higher density at atmospheric pressure.

2.6 Hydrogen transportation

The low energy density of hydrogen makes its transportation more expensive. However, there are a number of measures aimed at neutralizing this disadvantage: compression, liquefaction, transportation in a bound state. There are many branched networks of gas pipelines in the world that can be reoriented to transport hydrogen. Also there can be created the separate hydrogen transportation infrastructure with its own pipelines and shipping networks, allowing large-scale transportation of hydrogen. Each method has both advantages and disadvantages, and the decisive factors in choosing one or another option will be distances, volumes, geography.

Transportation of hydrogen mixed with natural gas through existing gas pipelines would significantly reduce the cost of creating a new transport infrastructure. In addition, this approach will reduce CO_2 emissions, although the price of gas delivery to consumers will increase due to a decrease in density. To implement this technology, it is necessary to further refine the national rules on the content of hydrogen in natural gas and to harmonize the rules between countries.

However, when mixing hydrogen and natural gas, a number of problems arise:

- Since the energy density of hydrogen is 3 times less than the energy density of natural gas, the energy intensity of the gas mixture decreases: with a hydrogen content in the mixture of 3%, the volume of energy of the mixture transported through the gas pipeline decreases by about 2% (Haeseldonckx/D'haeseleer 2007). Consequently, the volume of gas required to cover the needs of consumers in energy will increase. Similarly, industries that use the carbon contained in natural gas (for example, for metal processing) will increase gas consumption.;
- The combustion rate of hydrogen is much higher than that of methane. This increases the risk of flame spread. Also, the hydrogen flame does not burn as brightly. New flame monitors likely to be required for high mixing ratios;

- Hydrogen admixture can adversely affect the operation of equipment sensitive to gas composition (Abbott/Bowers 2014). It can also reduce the product quality of some industrial processes..

There are stages in the existing system that cannot withstand high levels of hydrogen. The biggest limitation is likely to be in the industrial sector, where many industrial facilities have not been certified to use hydrogen. For example, chemical companies that use natural gas as a feedstock may need to make adjustments to their work processes and renegotiate contracts with natural gas suppliers, as the plants require a narrow gas composition specification to operate. The sealing systems of operating gas turbines are not designed for hydrogen content and can withstand no more than 5% of its content in the gas mixture. A similar difficulty occurs with many gas engines, where the recommended maximum hydrogen content is 2%. To work with hydrogen-containing mixtures, existing turbines and gas engines require minor modifications. And the development of new equipment can already be carried out taking into account the possible work with hydrogen. But such changes will take time and money.

There are about 5,000 km of hydrogen pipelines in the world today compared to 3 million km of natural gas pipelines. These pipelines are operated by hydrogen producers and are used to transport hydrogen to the refineries and chemical industries. In America, the length of such pipelines is 2,600 km, in Belgium 600 km, and in Germany a little over 400 km (Adolf et al. 2017).

Pipelines are characterized by low operating costs and a service life of 40 to 80 years. The main disadvantages include high capital costs and the acquisition of land use rights. Therefore, to start work on the construction of hydrogen pipelines, investors must have confidence in the future demand for hydrogen and government support. Existing high pressure natural gas pipes can be converted to hydrogen transport if they are no longer used for their original purpose, but the suitability of the pipe for such changes will need to be assessed in each case depending on the type of steel and hydrogen concentration (Melaina et al. 2013). Recent studies show that the existing network of gas pipelines, with minor changes, is suitable for transporting a mixture of gases with a low hydrogen concentration. The main problem is that with equal energy value, hydrogen will occupy 3 times more volume than natural gas. Therefore, additional capacities may be required for hydrogen transport.

Hydrogen can also be transported in a bound state, for example, in the form of ammonia. Today, ammonia pipelines are already in operation and their construction is cheaper than the construction of pipelines for pure hydrogen.

The addition of hydrogen to the energy balance of states will allow to diversify energy imports, what creates an increased interest in using ships to transport hydrogen.

Today, there are no ships transporting pure hydrogen. The design of these ships will be similar to the design of ships transporting liquefied natural gas, and transportation will be carried out in a liquefied state. Although this will require large expenditures in a number of projects, this option seems to be optimal. It is assumed that these vessels will operate on hydrogen evaporating during transportation (approximately 0.2% of the total volume per day, similar to those operated by gas carriers). If there is no load at the port of destination, the ship will return empty.

Among all the considered options, the transportation of hydrogen in a bound state (in the form of ammonia) is the most developed option in terms of intercontinental transportation. This technology seems to be the simplest, since it allows to use tankers for oil products.

In all cases, shipping logistics chains require infrastructure, including storage tanks, liquefaction and regasification plants, and conversion and reconversion plants, to be built at loading and receiving terminals as needed.

2.7 Hydrogen consumers

Industry is the main consumer of hydrogen today. The main consumers of hydrogen (both in pure and mixed form) are: oil refining (33%), ammonia producers (27%), methanol producers (11%) and steel producers by direct reduction of iron ore (3%).

Currently, more than 60% of the hydrogen used in refineries is produced using natural gas. Reducing the allowable values of polluting emissions into the atmosphere will help raise the level of hydrogen use in oil refining by 7% to 41 million tons per year by 2030, although the policy of curbing the growth of oil demand may reduce growth rates. It is believed that the current oil refining capacity will be sufficient to meet the growing demand for oil, therefore, the growth in hydrogen consumption will be associated with existing facilities already equipped with hydrogen production units.

Demand for methanol and ammonia is forecast to increase in the short to medium term, opening up new opportunities to increase hydrogen production. More efficient use of resources by industry may reduce the overall level of hydrogen demand, but this will only partially offset the increase in demand. The existing technologies for producing hydrogen, whether it be “grey” or “green” hydrogen, are able to cover the additional growth in demand, which is predicted at around 14 million tons per year by 2030.

In the long term, the production of steel and high temperature heat will also increase the demand for low emission hydrogen. If the current technological problems will be solved, then the main issues will be to reduce costs and scale production. In the long term, it is technically possible to produce all primary steel using hydrogen, but this would require huge amounts of green electricity (about 2,500 TWh/year, or about 10% of global electricity production today) and would be economically viable at very low prices for electricity.

Although pure hydrogen is not commonly used today as a fuel for electricity generation, there are small exceptions. In Italy, a 12 MW hydrogen-powered gas turbine operates, and in Japan, in the city of Kobe, a hydrogen gas turbine provides heat and electricity to the local community. Today commonly used hydrogen-rich gases from steel, petrochemical and refineries. Reciprocating gas engines can run on gas with a hydrogen concentration of up to 70% (in terms of volume), and in the future it is possible to run on 100% hydrogen (Rahm et al. 2009). Gas turbines can also run on hydrogen-rich gases. In Korea, a 40 MW gas turbine at an oil refinery has been operating on gases with up to 95% hydrogen for 20 years.

Another option for hydrogen utilization is fuel cells, which convert hydrogen into electricity and heat to produce water without direct emissions. They show high electrical efficiency of over 60% and higher efficiency at partial load, making them particularly attractive for load balancing applications.

3 Research part

3.1 Transportation

Hydrogen is a flammable, colorless and odorless gas, which raises concerns about its safety, especially if a leak has not yet been detected and the gas accumulates in a confined space; it can eventually ignite and cause an explosion. In addition, hydrogen embrittlement of metal is a problem as it can damage pipelines and containers; thus allowing the penetration of hydrogen through the materials. The calorific value of hydrogen (141.8 MJ/kg at 298 K) is significantly higher than that of most fuels, such as gasoline, with a value of 44 MJ/kg at 298 K. At the same time, liquefied hydrogen has a lower energy density compared to with hydrocarbon fuel: 8 MJ/l for hydrogen versus 32 MJ/l for gasoline. This property requires large storage volumes compared to hydrocarbons. At the same time, the low storage temperature of liquefied hydrogen at atmospheric pressure (-253 °C) imposes additional risks. If leaked, frostbite is possible and, more dangerously, when hydrogen is mixed with oxygen contained in the air, an explosive mixture will form, which can lead to an explosion (Atilhan et al. 2021; El-Halwagi et al. 2020).

Energy systems of the future based on renewable energy technologies may rely heavily on hydrogen as a key element for large-scale storage, sector interconnection, and even electricity reconversion. Global demand for hydrogen is projected to grow from 70 million tons in 2019 to 120 million tons by 2024 (Capurso et al. 2022; Safari/Dincer 2020). Therefore, hydrogen pipelines are often used in power system optimization models as a large-scale transport option..

In the article «Design and optimization of a hydrogen supply chain using a centralized storage model» Seung-Kwon Seo and others are developing and optimizing the hydrogen supply chain from supplier to end user using a centralized storage model. The results showed that the centralized storage model is better than the decentralized storage model in terms of the present value of hydrogen. The cost difference between the two models is up to $132 million per year across the entire supply chain. The economic benefits of the centralized storage model are mainly achieved through the use of economies of scale in storage, due to which distributed areas of storage are combined together (Seo et al. 2020).

In the article «Modeling hydrogen networks for future energy systems: A comparison of linear and nonlinear approaches» Markus Reuß and others analyze two different types of pipeline network topologies (namely, star and tree networks) and two different fluid flow models (linear and non-linear).

The main result of this study is that a network with an increased number of branch pipe nodes significantly reduces the overall length of the pipeline, as well as costs, with the same system design approach. Accounting for non-linear pressure drop for costing with discrete diameters has shown additional cost advantages over linearized costing, which uses a fixed gas velocity to calculate flow. Topology optimization reduced pipeline investment by 37% (Reuß et al. 2019).

In the article «Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues» Marc Melaina and others have found that it is possible to transport a mixture of natural gas and hydrogen through pipelines without significant changes in the operation and maintenance of pipelines at relatively low concentrations of hydrogen in the mixture. Today there is no consensus on the permissible content of hydrogen in the mixture. Thus, the UK and the USA have some of the lowest legal restrictions among all countries - 0.1% compared to 10-12% (by volume) in Germany and the Netherlands (Staffell et al. 2019). According to studies, based on local conditions and the composition of natural gas, when the hydrogen content in the mixture is up to 5-15%, there are only minor problems compared to pumping traditional natural gas. Starting from 15%, more serious problems may arise related to pipeline materials, pumping safety, etc. (Melaina et al. 2013)

In the article «Analysis of compression and transport of the methane/hydrogen mixture in existing natural gas pipelines» Andrzej Witkowski and others have analyzed the process of compressing a mixture of H_2 and CH_4 and the safety of transportation in existing pipelines at various values of the volume fraction of H_2.

The addition of hydrogen to natural gas significantly reduced the total mass flow transmitted and the compressor power output..

The result of calculations of the sizes of hazardous zones around pipelines transporting a mixture of methane and hydrogen indicate that, compared with pipelines transporting natural gas with the same parameters, the range of zones is smaller. The risk zone for transporting pure hydrogen starts at a distance of about

500 m from the potential leak. For methane transport, it starts at a distance of more than 600 m (Witkowski et al. 2018).

In the paper «Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature» Joan Ogden and others show that technical limitations would make it difficult to use the existing natural gas system to deliver hydrogen fuel on the scale needed to achieve significant reductions in transportation-related greenhouse gas emissions. The future demand for hydrogen transport fuel is predicted to far exceed the ability of the natural gas system to deliver hydrogen as part of the mixture. In the long term, a separate hydrogen transport system will be required (Ogden et al. 2018).

The research «Cost assessment and evaluation of various hydrogen delivery scenarios» of Murat Emre Demir and Ibrahim Dincer showed, that:

- For large power plants, transporting H_2 through a pipeline network is the most cost-effective option at $2.73 per kg delivered H_2;
- For small power plants, H_2 delivery via non-liquefied semi-trailers is a viable option at $2.86 per kg H_2 delivered;
- Large-scale pipeline delivery is the most environmentally friendly transportation option (Demir/Dincer 2018).

In the research «Life Cycle Assessment of hydrogen transport and distribution options» Christina Wulf and others have analyzed different ways of transporting hydrogen depending on delivery volumes and distances. The researchers confirmed the thesis of the previous article that pipeline transport is the most environmentally friendly way. Also, for large volumes, pipelines are the economic preferred option, while for small volumes, road transport may be preferable. Sensitivity analysis showed that while some parameters remain open for discussion, the overall preference for pipeline transport over road transport is high (Wulf et al. 2018).

In the article «Design and maintenance of pipe networks transporting hydrogen pure or blended with natural gas» Guy Pluvinage and J. Capelle explore the topic of hydrogen embrittlement. This phenomenon, associated with the weakening of metal-metal atomic bonds and the modification of ductility, is characterized by a negative effect on mechanical properties. However, different mechanical properties do not change with the same intensity. The yield strength, tensile strength and fatigue endurance limit practically do not change. On the other hand, elongation at break, resistance to fatigue crack propagation is greatly reduced. These effects must be taken into account when designing and maintaining pipelines..

Hydrogen embrittlement has a strong effect on the time between inspections for two reasons: the allowable defect size is greatly reduced due to the decrease in fracture toughness, and the growth of defects due to fatigue is accelerated. Also, embrittlement increases with increasing hydrogen pressure (FM.C Silly sur Nied et al. 2019).

3.2 Storage

Today, there is a demand in the world for the creation of large-scale energy storage facilities to provide electricity during periods of high demand and accumulate surpluses during periods of low demand. This issue can be solved by storing energy chemically, for example in the form of hydrogen: in aquifers, salt caverns, depleted reservoirs of hydrocarbons in the so-called underground seasonal hydrogen storage (USHS). The use of hydrogen as an energy carrier is a promising solution for clean energy due to its environmental friendliness and high specific energy. Therefore, it is necessary to develop methods for high-capacity hydrogen storage, which will smooth out seasonal fluctuations in energy consumption. However, these technologies are not yet sufficiently developed for industrial applications (Heinemann et al. 2021).

From a geological point of view, underground formations are suitable for storing hydrogen, which will allow excess energy to be stored in the system, and then given back for re-electrification when it is most needed. As an illustration of the possible storage potential, the volumetric capacity of a hydrogen based flow battery system stores approximately 2.7 kWh/L of electrolyte, and therefore a depleted million barrel oil field would contain >3 TWh of electricity. This is equivalent to a 30-week run of a large offshore wind farm, far more than is needed to eliminate the outage problems associated with such a plant. Thus, it has been proven that only a few offshore gas fields are needed to store enough hydrogen to balance seasonal heating irregularities in the UK (Mouli-Castillo et al. 2021).

It is also possible to store hydrogen on the surface of solids (adsorption) or inside solids (absorption) (Simanullang/Prost 2022). When energy demand peaks, hydrogen can be recovered to generate electricity.

Thus, three potential hydrogen storage technologies can be considered depending on pressures and temperatures.

The first is the storage of liquefied hydrogen. This option requires low temperatures, since the boiling point of hydrogen at atmospheric pressure is −253 °C, and the density is close to 71 kg/m^3. This makes storing hydrogen at atmospheric pressure costly and problematic in terms of safety. It is necessary to store liquefied hydrogen in cryogenic vessels, the pressure in which can reach 25–35 MPa. Also, the volume of liquid hydrogen is about three times the volume of gasoline with a similar energy value, which requires large tanks (Hassan et al. 2021; Moreno-Blanco et al. 2019; Yanxing et al. 2019).

At pressures of 5-30 MPa and temperatures of 25-130 °C, hydrogen can be safely stored in underground geological formations (Andersson/Grönkvist 2019). For USHS, hydrogen must be transported to the wellhead. The hydrogen must then be compressed to be pumped at a pressure sufficient for underground storage.

Large-scale underground storage of natural gas has been implemented for many decades, with a total of 413 billion cubic meters of natural gas located in various geological formations in the following ratio: depleted gas fields (80%), underground aquifers (12%) and salt caves (8%) (Perry 2005).

Depleted fields are of interest for underground hydrogen storage due to their capacity, proven tightness, available fields performance data and existing infrastructure (Matos et al. 2019; Tarkowski 2019).

Both in liquid form and in the form of a compressed gas, hydrogen has a low density, which makes it difficult to store it in a porous medium. Hydrogen is lighter than water, what will create a strong buoyancy effect and water may rise up to the well, increasing the chance of hydrogen leakage. To avoid this, a buffer gas is used, often cheaper and with a higher density, such as carbon dioxide or nitrogen. This method is well known in the field of underground storage of natural gas (Cao et al. 2020).

Another underground storage option that can be used under certain conditions is the use of salt caverns as storage for high pressure gas (Gabrielli et al. 2020;

Hassanpouryouzband et al. 2021). Based on energy intensity (GWh) and discharge time, hydrogen storage in salt caverns can provide long-term energy storage on a scale sufficient to cover energy demand at peak times by conserving surplus energy during drawdowns. This solution has the advantages of the self-compacting nature of the salt and the ability to change the size and often the shape of the caves (A.S. Lord et al. 2014). However, the possible inaccessibility of salt caverns in the region of hydrogen production may be a limiting factor.

3.3 Installation of expander-generators for gas pressure energy recovery at gas distribution stations

The main reason for the loss of energy in the GDS is the pressure reduction mechanism by spending the energy of the natural gas flow to overcome the local resistance represented by the throttle body of the pressure regulator (PR) (Kargaran et al. 2013).

This previously lost energy of gas pressure can be redirected to perform useful work by converting pressure energy into mechanical energy of rotation of the expander rotor (Kostowski 2010).

According to the data on the loading of the "Sertolovo" gas distribution station, depending on the seasons in 2021, a graph of the amount of electricity generated during 2021 was built:

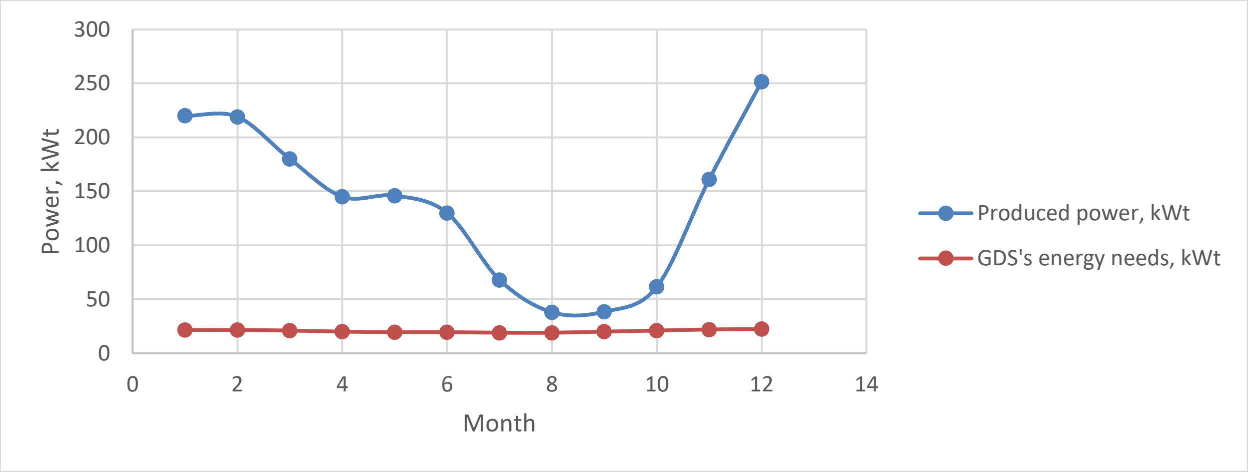


Figure 9: **GDS power generation capacity**

It can be seen from the graph that, regardless of the month, the amount of electricity generated exceeded the electricity needs of the GDS, even during the summer period of operation, when gas consumption was minimal. It can be concluded that with the introduction of the technology of an expander-generator set, it is possible to provide electricity to the GDS all year round, and with a large gas flow, an excess of electricity occurs, which makes it possible to provide electricity to other consumers (Fetisov et al. 2023).

The purposes and schemes for using expanders at reduction points can be different: for power generation, for gas liquefaction (Kumar/Singh 2023; Kumar et al. 2022; Mazumder et al. 2023), as part of cogeneration (Badami et al. 2017; Farzaneh-Gord/Sadi 2008; Leusheva/Morenov 2017), and so on.

Moreover, it is often economically and energetically expedient to include turbo expander units in the technological schemes of large reduction points (Badami et al. 2017; Danieli et al. 2020). Most turbine-type expanders are between 1 and 12 MW and require high gas flow and high pressure drop to operate.

There are various types of expanders: rotary, piston, screw and turbine. Turbine type is the most suitable for operation in GDS conditions, as they allow to work with high pressure drops and high flow rates.

In his scientific work "Methodology for the creation of autonomous turbine sources of electrical energy using the energy of compressed natural gas for the own needs of the gas transmission system of Russia" Fokin G.A. gives a schematic diagram of a microturbine generator set (Fokin G.A. 2015):

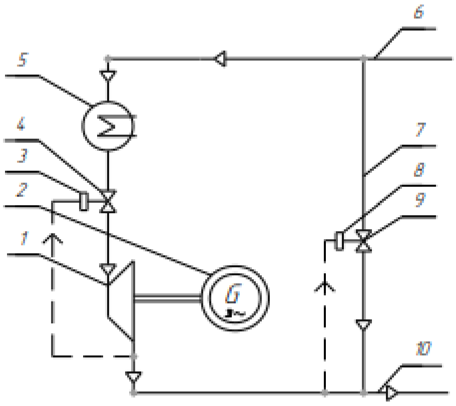


Figure 20: Schematic diagram of a microturbine generator set

1 – turbine; 2 – electric generator; 3 – pressure regulator; 4 – control valve; 5 – gas heater; 6 – high pressure gas pipeline; 7 – bypass pipeline; 8 – pressure regulator; 9 – bypass valve; 10 – low pressure gas pipeline.

In the article «Enhancing energy output in Iran's natural gas pressure drop stations by cogeneration» M. Farzaneh-Gord and M. Sadi conducted a comprehensive program to measure and account for the properties of natural gas at the inlets and outlets of all gas distribution stations in Khorasan province throughout the year. Based on these recorded data and the proposed system, the amount of energy received for all stations was calculated. It was found that on average ≈20 MW of electricity can be generated per year. The results also showed that the average annual mass consumption of natural gas at the considered stations is $78{,}26\ \mathrm{kg}\cdot s^{-1}$ and 2 W can be obtained per m^3/day of natural gas consumption.

Based on the averages of seven GDS in Khorasan province and the daily consumption of natural gas in Iran of $336\cdot10^6$ m/day, the total amount of energy obtained from the pressure exergy of natural gas flowing through the high pressure pipeline is predicted to be ≈672 MW (Farzaneh-Gord/Sadi 2008).

In the paper «Energy recovery from natural gas pressure reduction stations: Integration with low temperature heat sources» Borelli D. et al. write that lowering the process temperature in an energy recovery gas distribution station provides many benefits. All these factors prompted the authors to analyze the possibility of reducing the temperature of the regeneration process, in particular, by considering a two-stage expansion process, i.e. two turboexpanders installed in series.

The conducted study confirmed the feasibility and effectiveness of such a configuration. From a technical point of view, the operational functionality has been tested and analyzed.

As you know, when preheating the gas, the temperature of the process water is usually set at 85°C. With the new configuration, the temperature can be reduced to 55°C. However, operating under these conditions makes the risk of methane hydrate formation even higher, as it becomes easier to get into the hydrate zone in a shorter time. To this end, in this study, an accurate transient analysis was carried out for a typical winter scenario, the most suitable for this purpose. The results of the analysis show that the proposed new configuration does not lead to dangerous operation of the system, what means that the risk of formation of methane hydrate is excluded under normal operating conditions (Borelli et al. 2018).

In the article «A novel expander-depending natural gas pressure regulation configuration: Performance analysis» Xiong Y. and others propose a new configuration in which a screw expander replaces the throttle valve and turbine in a traditional gas distribution station, acting as a pressure regulator and pressure energy recovery machine.

The experiments were carried out at a stable inlet pressure of 0.6 MPa and an outlet pressure of 0–0.1 MPa, and for exergy analysis, a curve of the isentropic efficiency of a single screw expander depending on the volume flow was obtained.

The daily efficiency of the system can reach 25%, and more than 60 kWh of electricity can be generated per day, while the daily exergy efficiency of the expander reaches 37.02% (Xiong et al. 2018).

It is also possible to combine an expander with a Rankine cycle for the simultaneous production of electricity and hydrogen. The overall exergy efficiency of the combined system was 47.9% (Ghaebi et al. 2018).

In the paper «Performance optimization of turboexpander-compressors for energy recovery in small air-separation plants» Meng Yang and others are considering optimizing the performance of turboexpanders. The combined design of the turbo expander and coaxial compressor can improve system performance and further increase the isentropic coefficient by 7.1% under design conditions, resulting in an 8.1% improvement in cooling capacity and a 1.7% reduction in required heating power (Meng et al. 2023).

3.4 Electrolysis

Hydrogen is the most abundant element in the universe, and because of its reactivity, it only exists on Earth in the form of compounds such as water and organic materials (Osman et al. 2022). Like electricity, hydrogen is an energy carrier, not a source of energy; using it for renewable energy storage is critical as it can be stored, used and transported.

There are many ways to extract hydrogen from hydrogen-bearing materials, both hydrocarbon and non-hydrocarbon, such as photonic, electrical, chemical, bioenergy, thermal, and combinations of these methods together (Osman et al. 2020). While electrolysis offers a 100% renewable way to produce hydrogen, it accounts for less than 5% of global production (Han et al. 2021). Many studies claim that hydrogen production from renewable energy sources will become competitive in the near future. In addition, in all planned H_2 generation options, electricity is considered the main (Gutiérrez-Martín et al. 2021; Hota et al. 2023; Sun et al. 2023).

The traditional electrolysis system includes 2 metal electrodes separated from each other by a membrane and placed in an electrolyte solution (Davidson 2012; McCambridge 1988). When an electric current passes through the solution, hydrogen and oxygen begin to be released on the electrodes. To increase energy efficiency, electrodes are usually coated with a catalyst (Chaudhry 2015; Zhu et al. 2019).

The proton exchange membrane (PEM) along with the alkaline anion exchange membrane (AEM), paired with a concentrated potassium hydroxide solution, are the most common methods used in low temperature water electrolysis. The main advantage of this system compared to others can be called low cost, since catalysts from platinum group metals are not used here. However, this imposes a limitation on the hydrogen generation rate, which is quite low (Dvoynikov et al. 2021; Yu et al. 2019).

Membrane reactor technology is increasingly recognized as a promising way to expand pure hydrogen production. This option makes it possible to obtain hydrogen with a purity of at least 99.8% without additional gas purification (Jorschick et al. 2021).

However, hydrogen production would require large amounts of fresh water. The use of water in hydrogen production is associated with problems such as corrosion of the anode metal. The scientists reported a solution to this problem by developing an anode material in the form of a porous nickel foam collector coated with an active and inexpensive nickel-iron catalyst, which showed high conductivity and corrosion resistance. It is worth noting that the cost of water is typically less than 2% of the total cost of producing hydrogen by electrolysis (Milani et al. 2020).

In the work «Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review» (Buttler/Spliethoff 2018) Alexander Buttlera and Hartmut Spliethoff compare different electrolyzer types in terms of available power, nominal and part load performance, flexibility, life and investment costs.

Alkaline electrolysis is the most mature technology available commercially for over a century. It has the lowest specific investment and maintenance costs. Historically, the alkaline electrolytic cell was designed for stationary applications and must be adapted to new flexibility requirements. In contrast, PEM electrolyzers have a fairly high degree of flexibility. PEM cells offer some advantages over alkaline ones in terms of compact design (high current density), pressurized operation and flexibility. The PEM cell features shorter start times, especially when cold, and performance can vary over the entire load range. In contrast, the load range of the alkaline cell is limited to ≈20–25% due to the risk of explosive mixtures.

The solid oxide electrolyser is still in the pre-commercial stage. This type can improve the efficiency of hydrogen production and offers interesting features such as reversible operation and syngas production through co-electrolysis. The main advantages and disadvantages of electrolyzers are presented in table 1.

The purity of hydrogen obtained by electrolysis is very high, approx. 99.999 vol.% after drying of the product and separation of oxygen impurities (Abdin et al. 2020).

Type of electrolyzer	Operating temperature, ℃	Advantages	Disadvantages
Alkaline	40-90	Developed technology Inexpensive catalysts Cheap	Current density low Low partial load range Liquid electrolyte can cause corrosion Gas mixing
Solid oxide	500-1000	100% efficiency Base metal catalysts High pressure operation possible	No industrial designs Cumbersome system Fragile system due to ceramic catalysts

			Operation at elevated temperatures
PEM	20-100	High current density High gas purity High voltage efficiency Good partial load range	Mainly precious metal catalysts Aggressive sour environment

Table 2: Advantages and disadvantages of different types of electrolyzers

In the research «Recent Progresses in Electrocatalysts for Water Electrolysis» Muhammad Arif Khan and others have addressed the issue of catalysts. Noble metals are considered to be the best electrocatalysts, however, the associated problems such as high cost and low noble metal content hinder the commercialization of water electrolysis technologies. Reducing the amount of noble material catalysts can reduce the cost of hydrogen, what has been shown to make hydrogen energy economically competitive (Dawood et al. 2020). While improvements have been made to reduce noble metal levels by modifying material composition and morphology, or by replacing noble metals with base metal catalysts, progress has been insufficient..

In the case of alkaline electrolysis, various transition metal compounds such as those based on Ni, Co, Mn and Fe, as well as their oxides (MOx), phosphides (MPx), sulfides (MSx) and alloys (MM'), have been widely used in recent years in an attempt to replace noble metal catalysts in the electrolysis of water.

In the case of PEM electrolysis, base metal catalysts that are capable of providing efficient performance have not yet been discovered. This is because very few base metal catalysts are resistant to acidic electrolytes. However, although pure base metals are not suitable as catalysts, they can be used as dopants or carriers for noble metals (Khan et al. 2018). It is estimated that by 2050 the use of iridium in the PEM block can be reduced by 90%, platinum can be reduced by 75% (Bareiß et al. 2019).

In the article «The investment costs of electrolysis – Acomparison of cost studies from the past 30 years» Sayed M. Saba and others conducted a literature review to determine the change in water electrolysis costs and published rates between 1990 and 2017..

From a technological point of view, significant progress has been made in the last decade in the dynamic response and scalability of electrolyzers (from a few kW to several MW) (Parra et al. 2019). There has also been a significant reduction in electrolysis costs in recent years (Thema et al. 2019).

For alkaline technology, the spread of estimates in the 1990s ranged from 873 to 2347 $€_{2017}/\mathrm{kW}_{\mathrm{HHV \cdot Output}}$. Today's estimates of future investment costs (2030) are narrowed down to 787 and 906 $€_{2017}/\mathrm{kW}_{\mathrm{HHV \cdot Output}}$.

For PEM technology, the range of estimates in the 1990s ranged from 306 to 4748 $€_{2017}/\mathrm{kW}_{\mathrm{HHV \cdot Output}}$. Today's estimates of future investment costs (2030) are narrowed down to 397 and 955 $€_{2017}/\mathrm{kW}_{\mathrm{HHV \cdot Output}}$.

Experts expect that for alkaline technology, which is considered a mature technology, most of the cost savings will come from improved supply chains and increased production volumes, while for PEM, technological innovation will be an important driver of cost reduction. In particular, cost savings for PEM systems are expected to result from further technical improvements in flow fields, and current rate through increased cell areas, higher automation, and improved quality control methods (Saba et al. 2018).

Water electrolysis is a well developed technology and uses electricity from the grid and existing infrastructure. Current technologies are expected to supply the hydrogen market in the near future (Baykara 2018).

Due to the high cost of electricity, electrolysis today is unable to compete with alternative methods of hydrogen production, which include the reforming of natural gas and gasoline (Bartela et al. 2021).

Hydrogen production from fossil fuels is still cheaper compared to other production technologies. However, recent research shows that geothermal, biomass and nuclear electrolysis and thermochemical technologies are competitive and promising techniques that can replace traditional methods of hydrogen production, so a transition to pure hydrogen looks possible in the near future (El-Emam/Özcan 2019; Glenk/Reichelstein 2019).

Although the production of hydrogen by electrolysis of water is a promising solution, electricity consumption should be taken into account. If hydrogen is produced by electrolysis of water at an assumed efficiency of 60%, all of today's hydrogen demand requires 3600 TWh of electricity consumption, which exceeds the total annual electricity production in Europe (Yue et al. 2021).

In the paper «Advances in alkaline water electrolyzers: A review» Martín David and others note significant improvements in alkaline cell design:

- Reduced gap between electrodes to reduce ohmic losses;
- New membranes made of inorganic materials are being developed;
- Increased operating temperature, which increases the electrolytic conductivity and improves the kinetics of reactions on the electrodes;
- Electrocatalytic materials have been developed to reduce the overvoltage on the electrodes (David et al. 2019).

In the article «Hydrogen production by PEM water electrolysis – A review» S. Shiva Kumar and V. Himabindu note that PEM electrolyzers allow energy to be converted into high purity hydrogen. Also, this type of electrolyzers have a compact design, high current density (more than 2 A/cm^2), high efficiency, high speed and the ability to work at lower temperatures (20–80 ℃). In addition, the balancing of such electrolysis plants is very simple, which is a plus for industrial applications (Shiva Kumar/Himabindu 2019).

Scientists also offer exotic options for electrolyzers. In the research «Floating membraneless PV-electrolyzer based on buoyancy-driven product separation» Jonathan T. Davis and colleagues describe the design and performance of a scalable off-grid photovoltaic electrolysis device used to produce hydrogen by solar-powered water electrolysis. The electrolyser of this device has a simple membraneless design, which provides efficient operation with high product purity and without active electrolyte pumping. The key to the operation of this photovoltaic cell is a new electrode configuration consisting of mesh flow electrodes coated with catalyst on only one side. These asymmetric electrodes promote the release of H_2 and O_2 gaseous products on the outer surfaces of the electrodes, followed by separation of the separated bubbles under the action of buoyancy into separate upper collection chambers. The successful demonstration of this concept was confirmed by high-speed video and analysis of the composition of gas products using gas chromatography. Whereas the device based on asymmetric electrodes allowed a mixture of gases of only 1%, the control device based on mesh electrodes coated on both sides with a catalyst allowed 7%. The simplicity of this membraneless prototype, characterized by the absence of a membrane or actively pumped electrolyte, makes it attractive for low cost hydrogen production (Davis et al. 2018).

3.5 Unsolved scientific problems on the research topic

The main reason for energy losses at gas distribution stations is the pressure reduction mechanism by dissipating the energy of the passing gas flow to overcome local resistance in the form of a throttle valve (Sheikhnejad et al. 2020).

In addition, a significant decrease in the temperature of natural gas after its expansion in the expander should be taken into account (Sokovnin et al. 2022). Burner gas heaters are traditionally used to restore its temperature, and various secondary energy resources, such as renewable (Schipachev/Dmitrieva 2021) and low-potential energy sources, are considered promising (Barbarelli et al. 2018; Borelli et al. 2018; Xiong et al. 2018).

In the paper «Techno-Economic Assessment of Turboexpander Application at Natural Gas Regulation Stations» Kuczyński S. et al. conclude that seasonal fluctuations in gas consumption are the key factor negatively affecting the economics of turboexpanders. Their assessment showed that when the gas flow rate deviates from its nominal value (less in summer and more than the nominal value in winter), at which the expander efficiency is maximum, power generation drops sharply due to a decrease in efficiency (Kuczyński et al. 2019).

The least studied is the issue of gas flow pressure energy conversion at small gas distribution points, which have the worst conditions for the operation of recovery facilities. They are characterized by an extremely unstable flow due to uneven gas consumption by consumers. The flow rates of the pumped gas are small, the pressure drops are small, and the space is very limited, so the system must be compact. In this case, existing installations are not always able to provide stable operation at unstable flow and show economic feasibility.

Although, due to distribution over large areas, the energy intensity of individual small gas distribution points is small, their total energy potential is huge. The conversion of gas pressure energy into electricity by installing expanders is an effective solution for providing gas distribution facilities and electrochemical protection systems with energy and endowing them with the property of autonomy. Due to this, energy consumption and load on power lines will decrease, the costs of connecting to them will decrease accordingly, and the energy efficiency of the gas transmission system will increase in general.

Considering all of the above, the solution to this problem can be a combination of the functions of a pressure regulator and a disposal unit in the form of an expander-generator based on a volumetric expander. In addition to the fact that today there are practically no reduction and disposal systems for small reduction points, the novelty of this solution lies, firstly, in the use of an expander directly as part of a pressure regulator, which will make it possible to stably work out fluctuations in gas flow rates and pressures, as well as significantly reduce the dimensions . Secondly, in the use of volumetric expanders, which, due to ease of maintenance and the absence of the need for high-speed rotation at low flow rates and pressure drops, increase the overall reliability of the system (Diao et al. 2018).

The following problems of hydrogen production are also noted:

- New technologies; such as electrolysis and biomass thermochemistry need major improvement to be able to compete with conventional H_2 production methods such as steam methane reforming;
- Despite the abundance of starting material, technological limitations in the production process lead to higher costs.;
- H_2 generation is mainly due to non-renewable energy sources, which leads to an increase in CO2 concentration in the air (Abdalla et al. 2018).

In the article «Review and evaluation of hydrogen production options for better environment» Canan Acar and Ibrahim Dincer review the advantages and disadvantages of selected hydrogen storage systems, including chemical hydrides, compressed gas, cryogenic liquid, metal hydrides, and nanomaterials. A comparative assessment of the economic, environmental, social and technical performance and reliability of the selected storage systems was carried out. Among the selected storage options, nanomaterials score the highest with an average score of 8.40/10, followed by chemicals and metal hydrides with average scores of 6.80/10 and 6.60/10. , respectively. Liquefied gas has the lowest average score (3.40/10), followed by compressed gas (6.00/10). The reason for the poor performance of cryogenic liquids is the extreme temperature requirements and associated safety risks, which also increase their cost. In addition, the loss of hydrogen in this option is very high, especially compared to the other selected options. To minimize such losses, cryogenic systems must be well isolated, which also adds to the complexity and cost of the storage option. Thus, the cryogenic storage option has the lowest efficiency ratings in all categories: economic, environmental, social, technical and reliability. Similar to the cryogenic option, compressed gas has some operational requirements due to the high operating pressure, which can cause a safety issue that also affects system cost and social performance. Overall, nanomaterials appear to be a promising option for future hydrogen energy systems. This is because nanomaterials emit the least amount of harmful solid, liquid, or gaseous waste; have the highest efficiency with minimal losses and show high reliability (Acar/Dincer 2019). The main advantages and disadvantages of various storage methods are presented in Table 3.

Storage method	Advantages	Disadvantages
Chemical hydride	Well understood, reversible reactions and compact design	Waste generation and logistics, infrastructure change needs
Compressed gas	Existing and well established technology, availability and low cost	Very high pressure requires increased safety measures and costs, lower storage density compared to conventional fuels.
Liquefied gas	Existing and well-studied technology, higher densities compared to compressed gas	Very low temperatures increase cost, loss of stored hydrogen, energy intensity of

		the process, lower density compared to conventional fuels.
Metal hydride	Safe and modular operation with a wide range of applications, relatively high density	Disposal of used materials and problems with waste
Nanomaterials	High energy density	Early stage research and development, costs yet to be reduced

Table 3: Advantages and disadvantages of various hydrogen storage methods

In the paper «Hydrogen energy, economy and storage: Review and recommendation» J.O. Abe and colleagues note that one of the main keys to the full development of the hydrogen economy is the safe, compact, lightweight and economical storage of hydrogen. Conventional pressurized hydrogen gas storage system and liquid storage system create safety and cost problems; therefore, they do not meet the future goals of the hydrogen economy. Fortunately, metal hydride solid-state storage systems have shown great potential for storing hydrogen in large quantities in a reasonably safe, compact, and multiply reversible manner, and thus are becoming an increasingly attractive option for hydrogen storage. However, the feasibility of hydrogen storage systems has not yet been realized, as none of the existing metal hydrides meet all the main criteria, mainly due to low hydrogen storage capacity, slow kinetics, and unacceptable hydrogen uptake/desorption temperatures (Abe et al. 2019).

A new demonstration project will start in 2019. The HyCARE (Hydrogen CArrier) project aims to develop a 50 kg hydrogen storage tank using metal hydride by combining hydrogen and heat storage to improve energy efficiency and reduce the footprint of the entire system (Hirscher et al. 2020).

3.6 Promising proposals for solving identified scientific problems

In the article «Development of large scale unified system for hydrogen energy carrier production and utilization: Experimental analysis and systems modeling» Hirokazu Kojima and colleagues conducted an experiment on the world's largest system for the production, storage and disposal of hydrogen energy carriers in order to obtain basic data for the practical use of a system using renewable energy. In this system, an alkaline water electrolyzer is combined with hydrogenation reactors to produce methylcyclohexane. Since the behavior of the electrolyzer directly affects the hydrogenation reaction, the behavior of the 150 kW electrolyzer with fluctuations in power consumption was experimentally investigated. The battery voltage and hydrogen flow rate varied following the fluctuations in the input current, while the temperature response was slow due to the large heat capacity of the system.

A simulation model of an alkaline water electrolyzer was developed. According to the experimental result of electrolysis using a fluctuating electricity value, which reproduced the fluctuating power of a wind turbine at the same place, the hydrogen flow rate was well synchronized with the input electricity, and there was no significant time delay. The developed simulator predicts this experimental result very well (Kojima et al. 2017).

In the article «Mathematical Modeling of the Operation of an Expander-Generator Pressure Regulator in Non-Stationary Conditions of Small Gas Pressure Reduction Stations» Belousov A.E. and Ovchinnikov E.S. (Belousov/Ovchinnikov 2022) propose the use of an expander-generator simultaneously as an exergy exchanger and a regulator; schemes of reducing lines equipped with an expander-generator-regulator have been developed. The flow separation occurs immediately after the safety shut-off valve 5. Part of the flow goes to the expander 6, where expanding it loses pressure and does useful work, while the other part is reduced on the pressure regulator 8. The flow separation occurs in relation to the degree of opening of the regulator 8. Then the flows are combined and through the safety relief valve 13 go to consumers or further along the network. This design of the regulator assembly allows the use of a volumetric expander as the main pressure regulator..

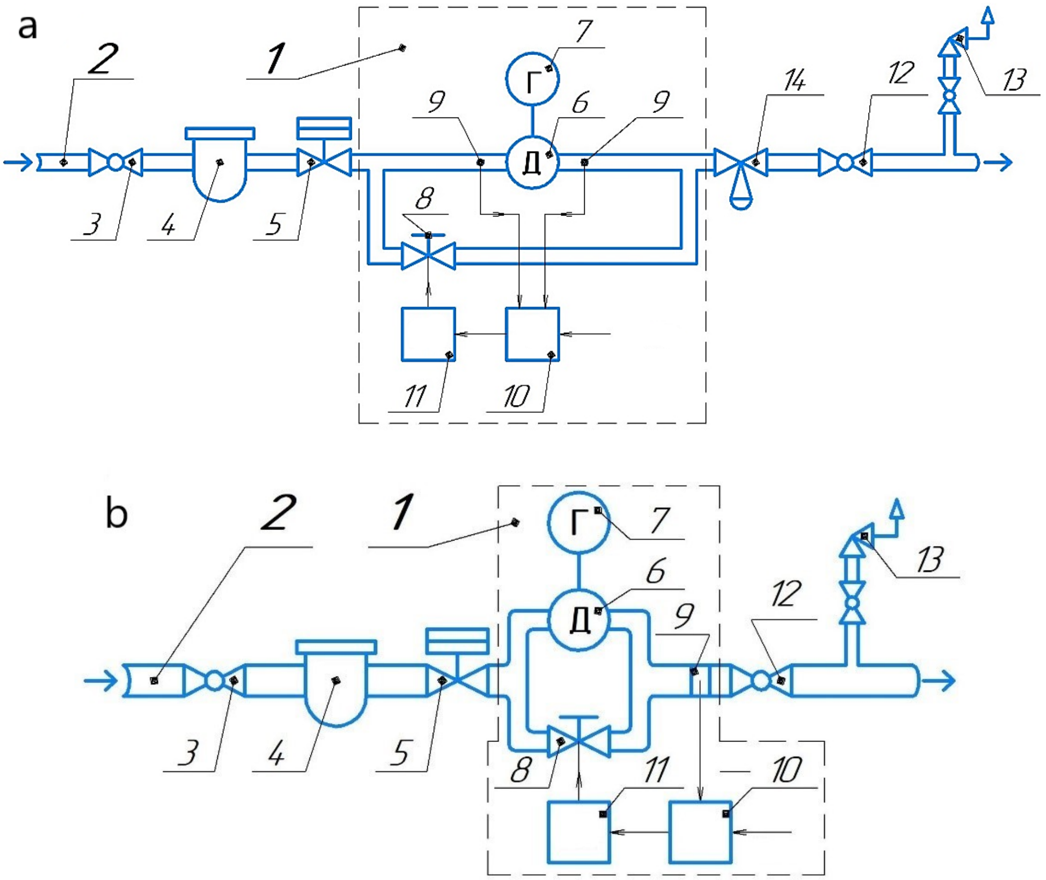


Figure 11: Schematic diagram of the gas reduction line at the reduction point with the expansion type EGR system with stabilization by the control system

a) pressure drop before and after the expander; b) pressure at the outlet of the GRP.

1 – EGR; 2 – reduction line; 3 – inlet shut-off valves; 4 – filter; 5 – safety shut-off valve; 6 – volumetric expander; 7 – electric generator; 8 – control valve; 9 – pressure sensor; 10 – controller; 11 – actuating device of the control valve; 12 – outlet valves; 13 – safety relief valve; 14 – pressure regulator.

The systems under consideration use different parameters to stabilize the operation:

- stabilization of the pressure drop across the expander, which keeps the speed of the expander rotor constant, but then it is necessary to install an additional regulator to maintain the pressure at the outlet of the gas distribution point (Fig. 12a);
- pressure stabilization at the GDS outlet directly by the expander control system, without additional regulators (Fig. 12b).

The most important parameters were chosen as target parameters during regulation. The rotation speed affects the quality of the generated electricity, and the output pressure affects the safety of the operation of the final equipment..

With a drop in gas consumption, the outlet pressure of the reduction point increases and, as a result, the pressure drop across the expander decreases, and the rotor speed decreases. The controller 10 responds to a change in the controlled parameter and sends a signal to close the control valve 8 until the speed of rotation of the expander rotor is restored.

With an increase in gas consumption, the outlet pressure, on the contrary, drops and then, to maintain the rotation frequency at the same level, the control valve 8 already opens.

With an increase and decrease in inlet pressure at the gas distribution point, the system reacts in a similar way.

In case of failure of the hydraulic stabilization system, it is possible to regulate the gas supply through the expansion machine, by increasing or decreasing the rotor speed (Xiong et al. 2018).

Gas cooling due to expansion in the expander in the specified range of pressures and flow rates is not critical, therefore gas heating is not required.

The proposed expander-generator pressure regulator simultaneously performs the functions of a pressure regulator with remote control and a power generation unit for the needs of small reducing stations (telemetry, remote control, lighting).

The main task of reduction points is to maintain a certain level of outlet pressure, but at the same time, the quality of the generated electricity at an unstable frequency of rotation of the expander rotor must also be ensured at a certain level..

The ability of the expander-generator and the proposed stabilization systems to operate stably under conditions of non-stationary gas consumption by consumers and pressure changes in front of the GDS is considered in the experimental part of the dissertation.

3.7 Research methodology

To study the operation of the reduction line with the installed volumetric expander, a series of experiments was carried out on the installation created on the basis of the patent of the Russian Federation 2620624 and the application for a patent of the Russian Federation No. 2017141301 dated 11/27/2017 (Belousov/Kabanov 2017).

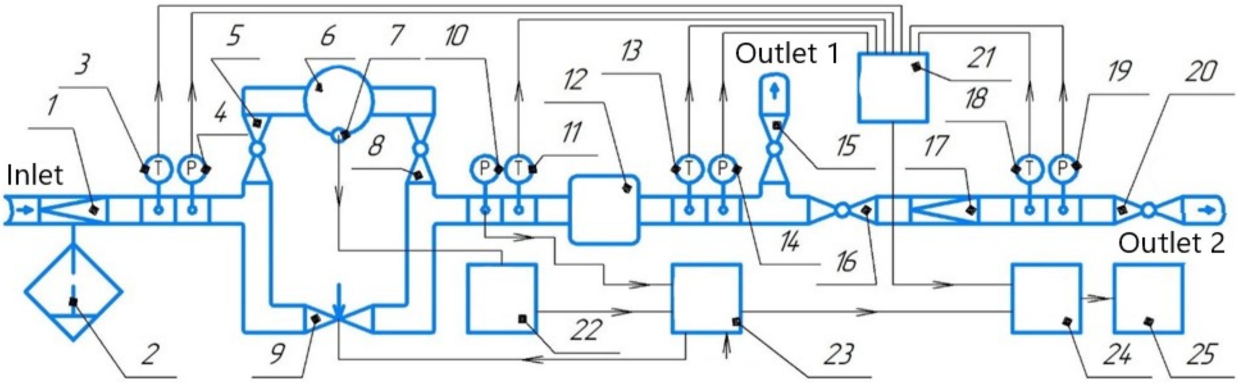


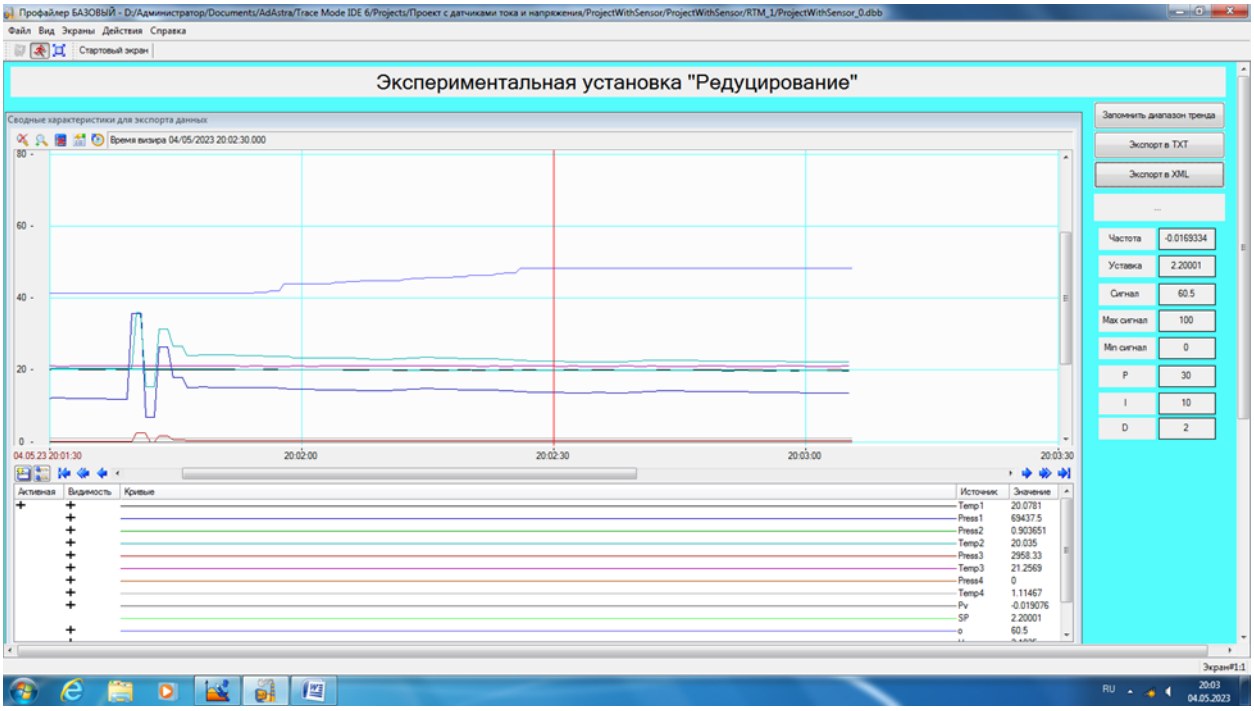
Figure 12: **Scheme of the experimental setup**

Figure 13: **Experimental setup**

The scheme of operation of the installation is as follows. The air compressed by the compressor enters the reduction line, where the pressure is reduced by dissipating the energy of the flow at the pressure regulator 1 and excess moisture is removed from the flow by the filter-separator 2. Then the temperature and pressure sensors 3 and 4 take data from the passing flow, after which it is divided into 2 parts in proportion depending on the degree of opening of the control valve 9. The first part passes through the vane expansion machine 6, where it expands and loses pressure, the second is reduced on the control valve 9. Then the pressure and temperature of the combined flow are measured by sensors 10 and 11. Then the flow passes through the receiver 12, once again passes the data measurement by sensors 13 and 14 and exits into the atmosphere. Gas can be released into the atmosphere in two ways. When valve 16 is closed, air is removed from the system by valve 15, with the help of which disturbances are created, simulating the unstable gas consumption. If the valve 16 is open and the valve 15 is closed, then the gas passes through the static pressure regulator 17, after which pressure and temperature are measured by sensors 18 and 19. At the outlet there is a valve 20 for discharging gas into the atmosphere and simulating disturbances.

The tachometer 22 converts the signal from the proximity sensor and sends it to the first input of the proportional-integral (PI) controller 23. The signal from the pressure sensor 10 located behind the expansion machine comes to the second input of the PI controller 23. When changing the speed of the expander rotor, the electric actuator of the control valve 9 receives a signal to change the degree of opening from the PI controller 23 to return the value of the speed of rotation of the expander rotor to the setpoint.

Then the PI controller collects data from pressure and temperature sensors, frequency rate and sends them to a personal computer, where these data are visualized and exported for further work using the SCADA Trace Mode program.


Профайлер БАЗОВЫЙ - D:/Администратор/Documents/AdAstra/Trace Mode IDE 6/Projects/Проект с датчиками тока и напряжения/ProjectWithSensor/ProjectWithSensor/RTM_1/ProjectWithSensor_0.dbb

Экспериментальная установка "Редуцирование"

Сводные характеристики для экспорта данных

Время визира 04/05/2023 20:02:30.000

Частота	-0.0169334
Уставка	2.20001
Сигнал	60.5
Max сигнал	100
Min сигнал	0
P	30
I	10
D	2

Источник	Значение
Temp1	20.0781
Press1	69437.5
Press2	0.903651
Temp2	20.035
Press3	2958.33
Temp3	21.2569
Press4	0
Temp4	1.11467
Pv	-0.019076
SP	2.20001
o	60.5

Figure 14: The working screen of the SCADA Trace Mode program

An electrolyzer is additionally connected to the system to conduct experiments on hydrogen production:

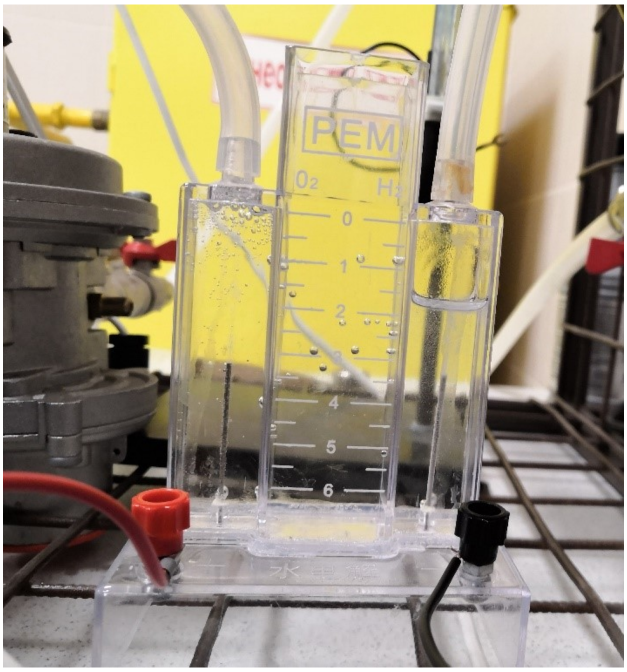


Figure 15: Electrolyzer

The experiment was carried out with 1% NaOH alkali solution:

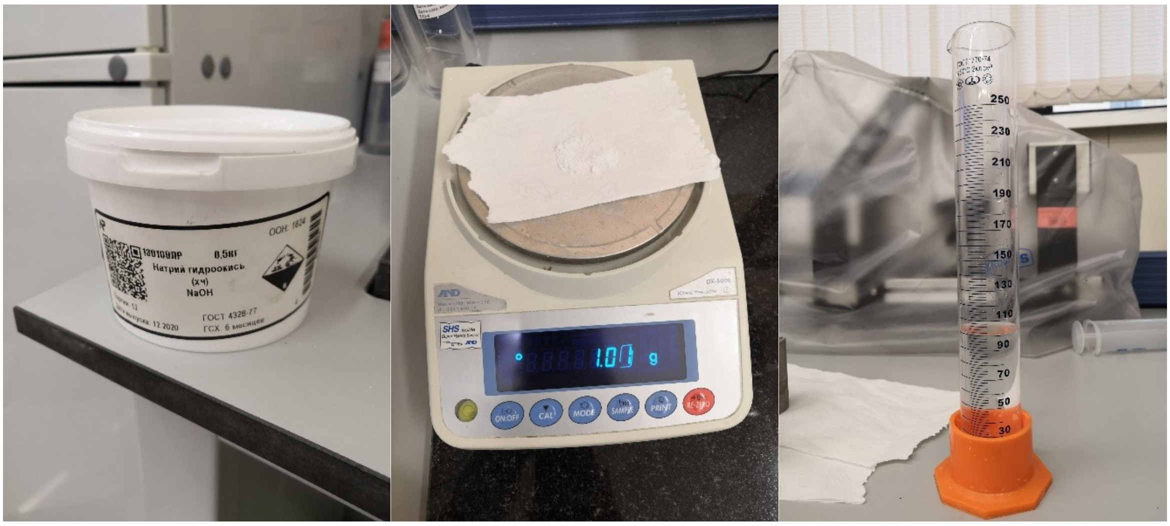


Figure 16: Alkali solution used in the experiment

A manometer was used to determine the volume of released hydrogen:

Figure 17: Manometer

The height of the displaced liquid column indicates the hydrogen pressure, the volume of the manometer is known. According to the equation of state of the gas, we determine the masses of hydrogen and the volume under normal conditions.

The installation maintained the pressure at the outlet of the reduction line using a standard pressure regulator 17 with its preliminary decrease in the expander 6, the rotor speed of which is maintained constant. In this case, valve 15 is closed and the gas flow exits through the outlet. 2, PI controller 23 works according to the frequency setting ω_0.

3.8 Theoretical and experimental studies

A number of disturbances were created, simulating non-stationarity in the operation of gas distribution points, to assess the stability of the operation of the expander-generator unit system:

1) reduction of mass gas withdrawal by consumers by 30%;
2) increase in mass gas withdrawal by consumers by 30%;
3) reducing the inlet pressure of the reduction point by 10%;
4) increase in inlet pressure of the reduction point by 10%.

In any operating mode, the stabilization system, maintaining the set frequency parameter, bypasses through the control valve the amount of gas that exceeds the expander flow rate. The temperature under the conditions under consideration is an uncontrollable factor that depends on the pressure. Thus, we can say that the frequency of rotation of the expander rotor $\omega^e = f(p_1, p_2)$ is a function of only two variables, pressures before and after it

The values of the coefficients for the PI controller taken in the experiment are reflected below:

Disturbance	**Value**	K_p	K_i
decrease in gas extraction	-30%	0,1	0,1
increase in gas extraction	+30%	0,05	0,25
decrease in pressure before EGR	-10%	0,5	0,5

pressure increase before EGR	+10%	0,005	0,1

Table 4: Values of the gain factors of the PI control law

In both cases, both with an increase and a decrease in gas consumption, the regulator based on a volumetric expander correctly handle the resulting oscillations. Indicators of the frequency of rotation of the expander rotor and the pressure at the outlet of the GRP do not leave the permissible limits.

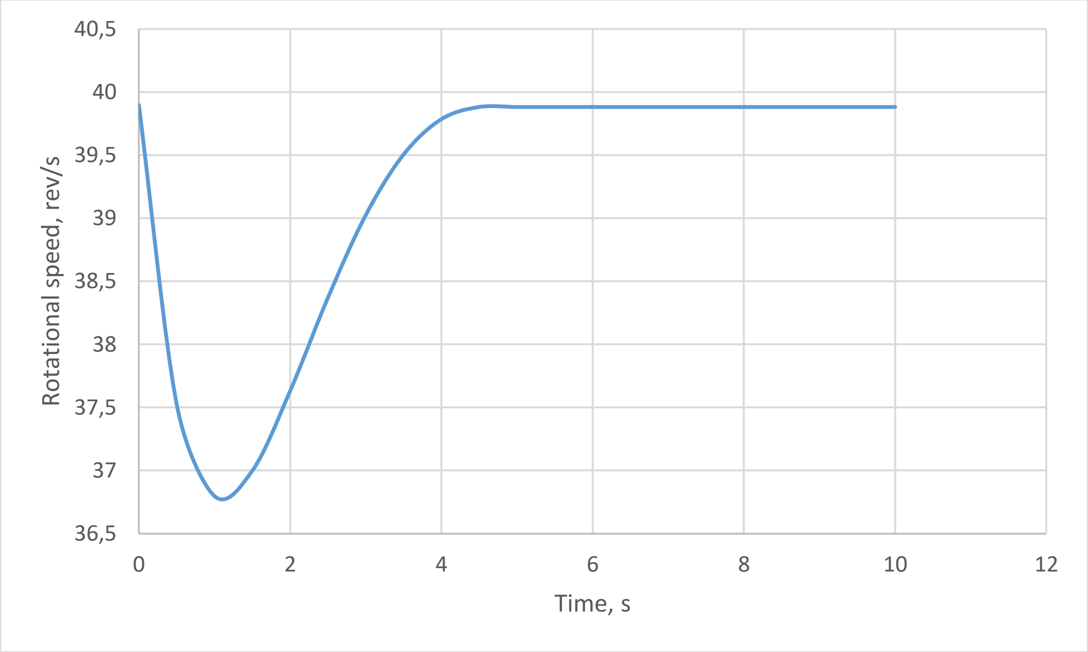


Figure 18: Drop in gas extraction by consumers: rotational speed of the EGR

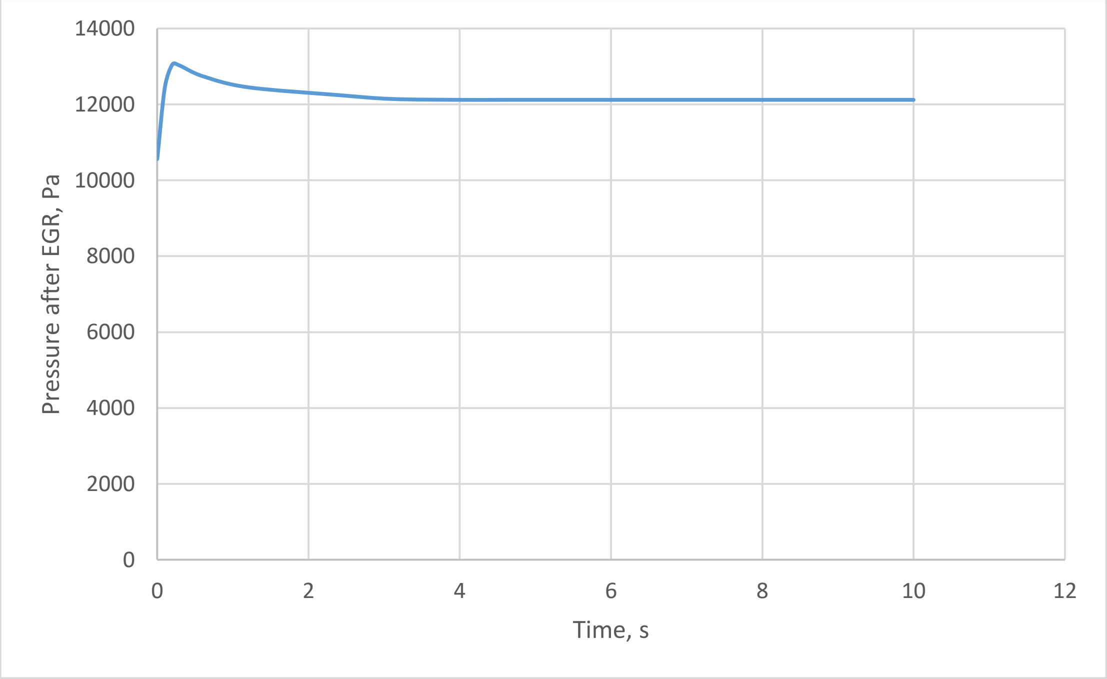


Figure 19: Drop in gas extraction by consumers: pressure at the outlet of the EGR

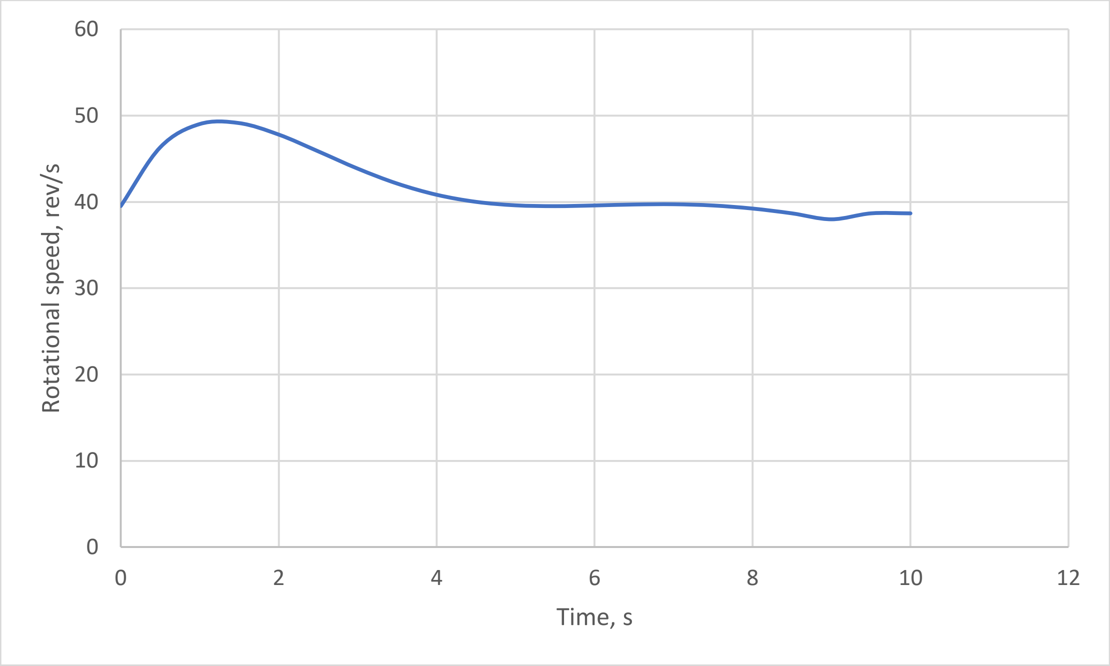


Figure 20: Growth of gas withdrawal by consumers: rotational speed of the EGR

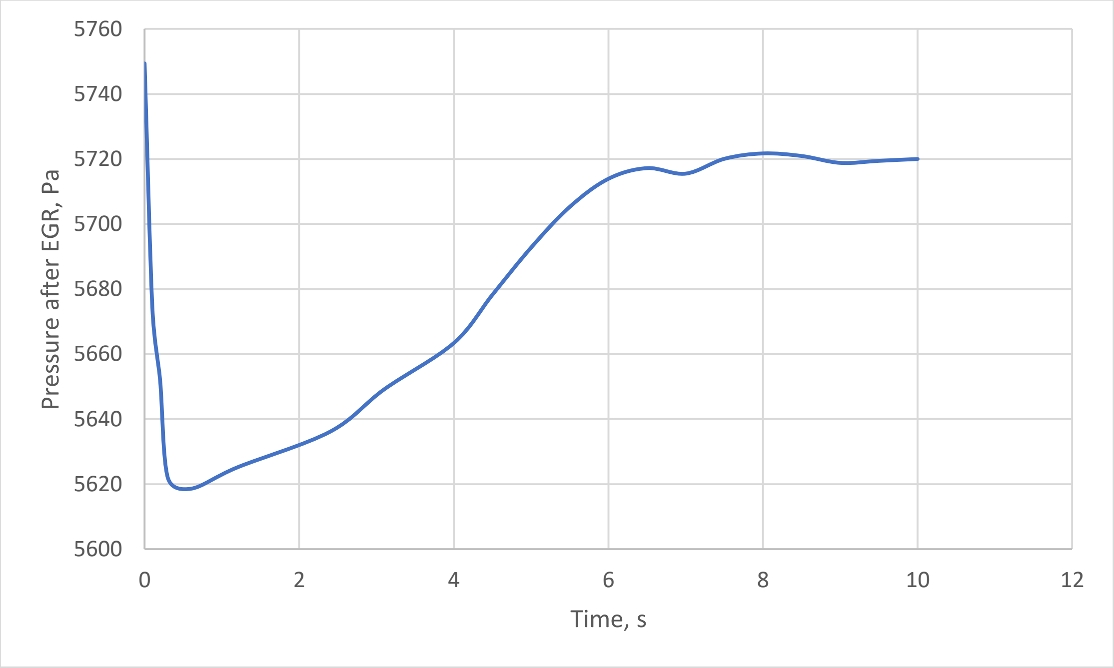


Figure 21: Growth of gas withdrawal by consumers: pressure at the outlet of the EGR

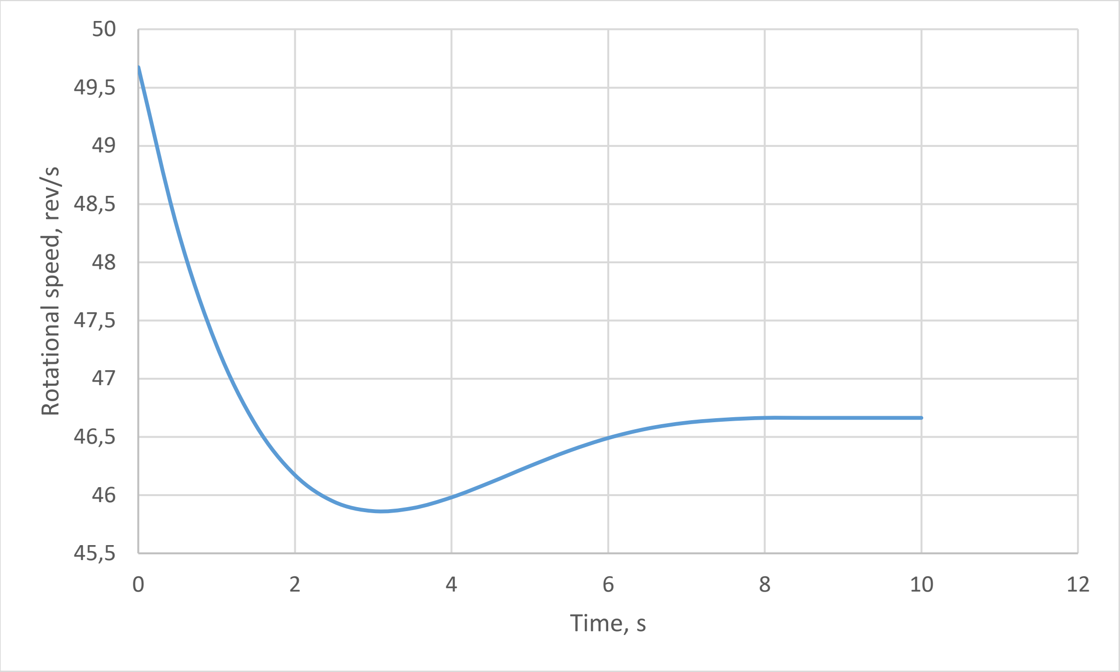


Figure 22: Pressure drop in the supply pipeline: rotational speed of the EGR

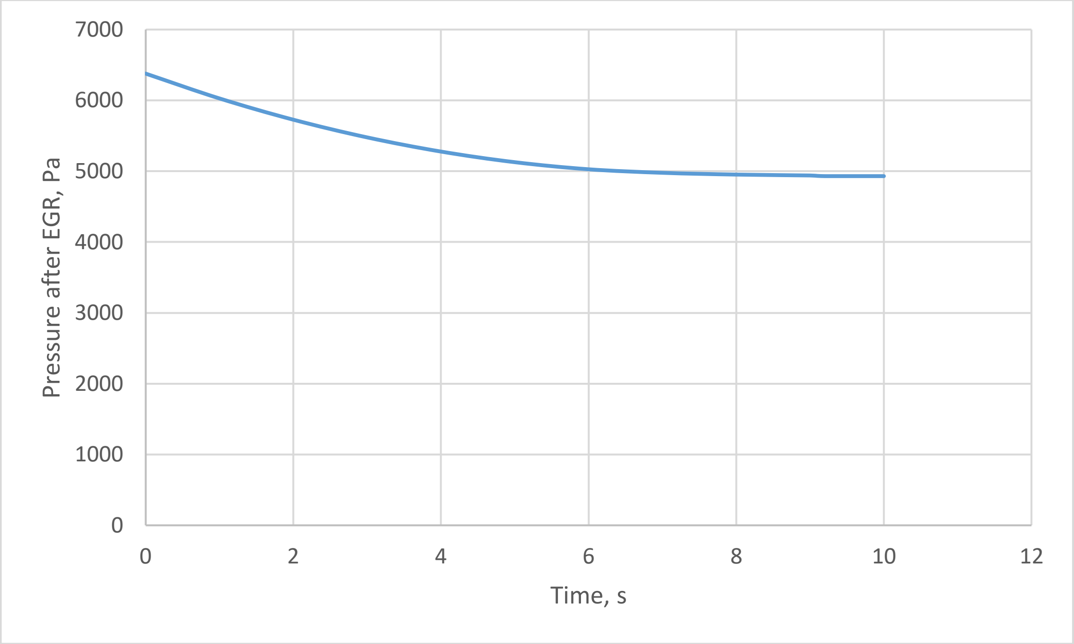


Figure 23: Pressure drop in the supply pipeline: pressure at the outlet of the EGR

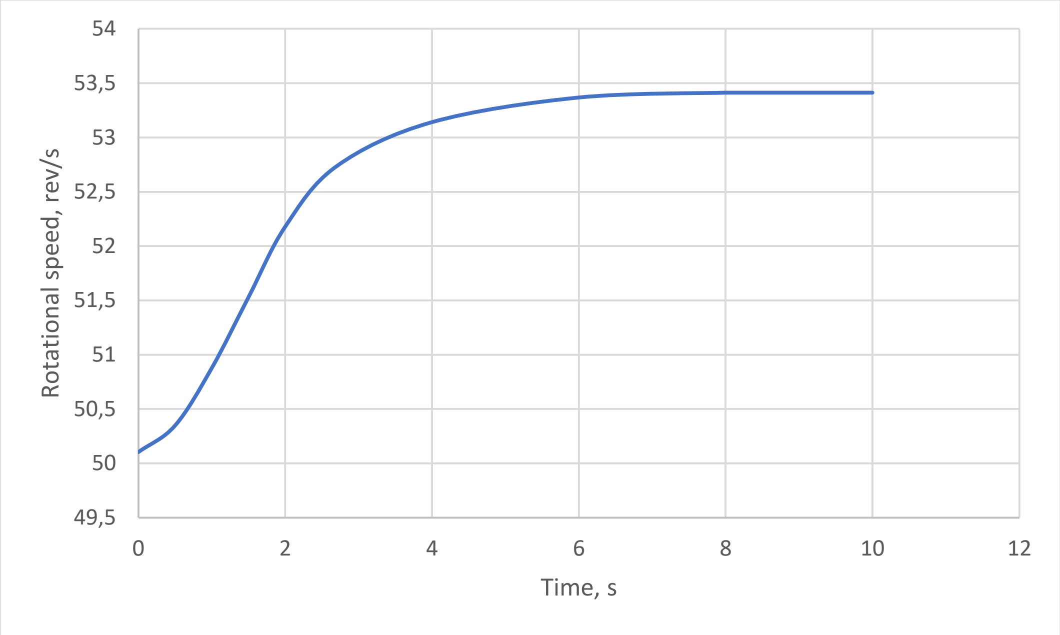


Figure 24: **Pressure increase in the supply pipeline: rotational speed of the EGR**

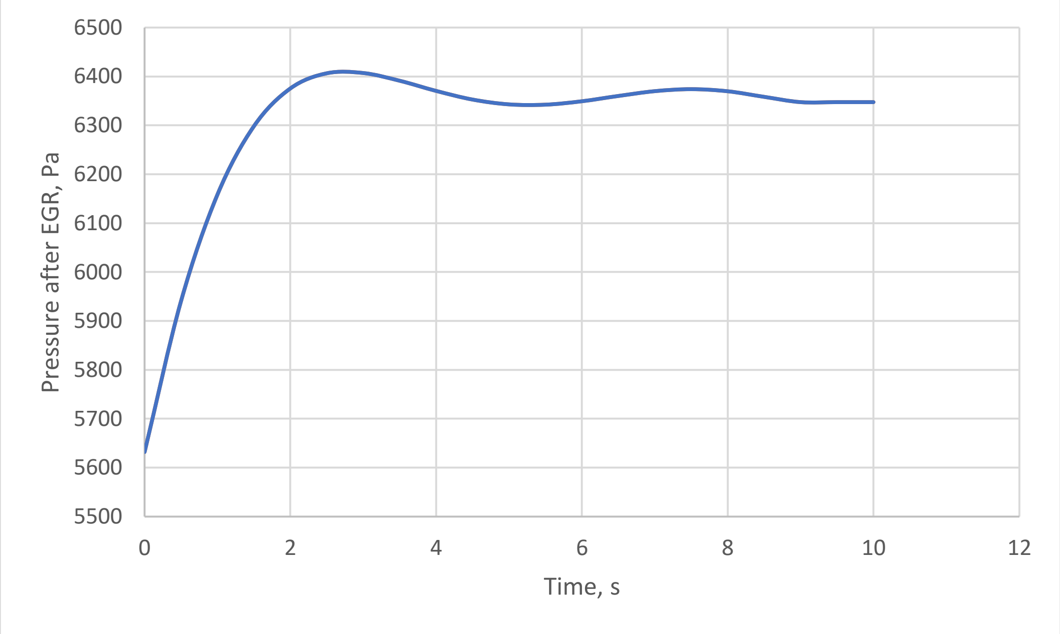


Figure 25: **Pressure increase in the supply pipeline: pressure at the outlet of the EGR**

Then an experiment was carried out to determine the amount of hydrogen obtained by lowering the gas pressure in the installation. First, a theoretical evaluation was carried out.

In 1833-1834 the English scientist Michael Faraday discovered the quantitative laws of electrolysis, establishing the relationship between the amount of electricity passed through the electrolyte q, the mass m and the chemical nature of the substances involved in the process:

$$m = k_e q \tag{4}$$

where

$$k_e = \frac{M}{nF} \quad (5)$$

k_e – electrochemical equivalent; *M* – molar volume of the substance released at the electrode, $\frac{m^3}{mole}$; *n* – the number of electrons involved in an electrochemical reaction; *F* = 96485,3 – Faraday constant, $\frac{C}{mole}$. Knowing the magnitude of the current I and its flow time t, we transform formula (2) and calculate the theoretical (maximum) amount of hydrogen (or oxygen) obtained by electrolysis of water:

$$V_{theor} = \frac{MItc}{nF} = \frac{MN_etc}{nFU} \quad (6)$$

где V_{theor} – theoretical volume of released gas, m^3; *I* – amperage, A; U – voltage, V; c – number of electrolyzer cells.

The experiment was carried out under the following conditions: $P_0 = 73\ kPa$; $P_2 = 32\ kPa$; $T_0 = 293{,}15\ K$; $Q_g = 0{,}15\ \frac{m^3}{min}$; $M = 0{,}002\ \frac{m^3}{mole}$; $n = 2$; $U = 2\ V$; $t = 45\ min$; $\mathrm{c} = 1$.

Theoretically, 0.06 liters of hydrogen can be produced in 45 minutes. As a result of the experiment, it 0.048 liters were obtained, what confirms the possibility of developing this model in further studies.

3.9 Analysis of the results of the study

Disturbance	**Value**	**Frequency stabilization**
		duration, s
drop in gas consumption	-30%	4,0
gas consumption growth	+30%	4,5
pressure drop before expander	-5%	7,2
pressure rise before expander	+5%	7,0

average transient time	5,675

Table 5: Duration of transients

Fluctuations in the value of the inlet pressure on the reduction line have a greater impact on the operation of the system than fluctuations in gas withdrawal by consumers. When implementing regulation in order to return the value of the speed of rotation of the expander rotor to the set value, it is not possible to return it to its original value, although it does not leave the allowable range of change $\Delta = 10\%$.

In both variants of disturbances, both with inlet pressure fluctuations and with changes in gas withdrawal by consumers, pressure fluctuations behind the expander-generator unit do not go beyond ± 25% range, what also confirms the system's ability to work out emerging disturbances and stabilize the system.

It is important to note that the characteristics of the equipment used in the course of setting up the experiments have a strong influence on the transient processes that occur during disturbances in the system. Accordingly, in real conditions, other quantitative values of the system operation can be obtained than those shown in the graphs. But qualitatively, the nature of the processes will remain, as well as the effective operation of the system for processing disturbances.

The experimental data obtained confirm the efficiency of natural gas reduction by converting flow pressure energy into electricity by installing expander-generator units in the gas distribution system.

The possibility of utilizing pressure energy to produce hydrogen at a gas distribution station is also confirmed. The obtained experimental data on the volume of gas production confirmed the calculations using the proposed model for estimating the potential volumes of hydrogen production in industrial conditions.

4 Feasibiliity study

A necessary condition for the implementation of the project is its payback. This section discusses the issue of economic feasibility of obtaining hydrogen at a gas distribution station by converting pressure energy into electricity.

4.1 Initial data

Research by OOO “Gazprom energo” shows that it is possible to install turbo-expander generators with a total capacity of up to 550 MW at gas distribution stations of PAO "Gazprom". The capacity of 80% of the installations is 0.3-4 MW, 15% is 4-9 MW and the remaining 5% can provide a capacity of 10-17 MW.

№	Name	P_{in_av}	P_{out_av}	T_{in_av}	T_{out_av}	Q_{av}	P_{in}/P_{out}	N_e
		kgf/cm^2	kgf/cm^2	C	C	m^3/h		kWt
1	Novy Urengoy 1	33,2	3,5	5	-10,1	37538	9,48	918,22
2	Nadym	33,1	8,8	5	-6,7	25092	3,76	391,99
3	CS Long-Yuganskaya	44,8	2,9	5	3	956	15,45	27,58
4	Harp	38,7	3,8	5	11,9	3910	10,18	96,87
5	Novy Urengoy 2	41,9	9,5	5	4,5	22317	4,41	423,98
6	Obskaya	47,8	4,1	5	6,1	3015	11,65	84,52
7	Pangody	35,9	1,7	5	3,5	7290	21,12	228,44
8	Salekhard	35	3,6	5	5,4	21484	9,72	509,87
9	Labytnagi-1	34,4	8,8	5	5,7	10864	3,91	172,23
10	Labytnagi-2	36,2	3,7	5	10,7	8445	9,78	205,66
11	Aksarka	48,1	25,1	5	8,6	2689	1,92	21,41

Table 6: Power values

Table 6 presents the calculation data for potentially received capacities at gas distribution stations. 64% of gas distribution stations allow installing expanders with a capacity of 100-900 kW, and the remaining 36% can potentially produce up to 100 kW and are of less interest in terms of installing turbo-expander units.

№	Type of instalation	Power, kWt	Productivity, nm^3/h	Power kW per 1 Nm^3/h
1	SEU-10	50	10	5,00
2	SEU-20	100	20,5	4,88
3	SEU-40	200	41	4,88

4	BEU-125	625	125	5,00

Table 7: Characteristics of industrial hydrogen generators

As can be seen from the table, today the cost of electricity for the production of 1 cubic meter of hydrogen is ≈5-6 kWh, including operations for water preparation and gas purification. So for the production of 1 m^3 hydrogen per hour, it is necessary to supply a current with a power of 5 kW. Then, when installing a minimum power expander with an indicator of 100 kW minus 20 kW for stations own needs, hydrogen is produced in a volume of 16 m^3/h. When installing expanders with a power of 900 kW, this value can reach up to 180 m^3/h

№	Type of instalation	Working pressure, kgf/cm^2
1	SEU-10	10
2	SEU-20	10
3	SEU-40	10
4	BEU-125	10

Table 8: Operational pressures of hydrogen generators

As can be seen from the table, the proposed models of modern industrial hydrogen generators make it possible to produce hydrogen under pressure with a pressure of 10 bar, which makes it possible to exclude the installation of the additional compressors.

It is proposed to pump hydrogen into cylinders and send it to end users. This approach allows solving the problems of power supply to remote settlements that are not connected to the power supply network. Hydrogen can be used as a fuel for generators, and fuel cells can also be installed at such points, which, as a result of chemical reactions, produce electricity. The elements work on hydrogen and oxygen, which simultaneously solves the problem of using oxygen released during the electrolysis process..

To fill cylinders with hydrogen, it is necessary to additionally equip the GDS with cylinder filling stations.

Below is a table with specific capital investments per unit of power for industrial electrolyzers of domestic production.

№	1	2	3	4
Type of electrolysis plant	SEU-10	SEU-20	SEU-40	BEU-125
Power of the electrolysis plant, kW	50	100	200	625
Specific capital investments, thousand rubles/kW	133,9	85	55,9	31,8
Productivity, m^3/h	10	20,5	41	125

Table 9: Economic indicators

Further economic calculation will be carried out for the performance of the Salekhard gas distribution station. To begin with, it is necessary to take into account the savings in electricity to meet the station's own needs due to an autonomous power supply system.

Gas distribution points belong to consumers with a low voltage level of the first price category with a power of up to 150 kW, as of March 2023, the cost of 1 kWh is 7.88 rubles. without VAT. As a rule, the total power consumption is within 20 kW. This means that the annual savings of the station on electricity to meet its own needs will be:

$$Q_e = 7{,}88 \cdot 24 \cdot 365 \cdot 20 \approx 1\,381\,000\, rub.$$

Taking into account the cost of electricity for the production of 1 cubic meter of hydrogen is within ≈5-6 kWh, in the conditions of the Salekhard station, it is possible to obtain 100 cubic meters of hydrogen per hour. Taking a selling price of 65 rubles per cubic meter, we get an annual profit of:

$$Q_{pr} = 65 \cdot 100 \cdot 24 \cdot 365 = 56\,940\,000\, rub.$$

Next, capital and operating costs are determined. First, the approximate cost of the necessary equipment is calculated.:

Equipment	Quantity	Cost, rub.

Expander	1	5 941 155
Electric generator	1	32 878 453
Reduction gear	1	30 000
Electrolyzer	3	33 540 000
Separator	1	549 000
Scrubber	1	240 540
Condenser	1	321 188
Catalytic purification reactor	1	130 560
Dehumidifier	1	206 000
Total:		73 837 000

Table 10: Equipment cost

The cost of construction and installation works at the Salekhard GDS will be approximately 2 590 000 rubles.

The cost of design work is determined in accordance with the “Methodology for determining the cost of design work depending on the cost of construction. MPP-4.8.02-18". The cost of design work, determined in accordance with this methodology, takes into account the development of design and working documentation. The distribution of the cost of the main design work by the types of documentation being developed is given in the table below:

№	Types of documentation	Share of the cost of the main design work, %
1	Project documentation	40
2	Working documentation	60
3	Design and working documentation	100

Table 11: Distribution of the cost of the main design work

The basic cost of work, depending on the cost of construction, is determined by the formula:

$$C_{pr(b)} = \frac{C_{con(b)} \cdot \alpha}{100} \cdot PC_i \qquad (7)$$

где:

$C_{pr(b)}$ – base cost of project work;

$C_{con(b)}$ – base construction cost;

α – standard cost of project work;

PC_i – the product of correction factors that take into account complicating (simplifying) factors and design conditions. The product of all coefficients K_i, except for the coefficient that takes into account the reduction in design time, should not exceed the value of 2.0.

The base cost of construction, taken to calculate the base cost of design work, includes the cost of construction, installation work and the cost of equipment:

$$C_{con(b)} = 73\,837\,000 + 2\,590\,000 = 76\,247\,000 \text{ rub.}$$

In the case when the base cost of technological equipment is more than 25% of the base cost of construction and installation works, to determine the value of the “α” standard and calculate the base cost of design work, the base cost of construction and installation works (excluding the cost of process equipment) is taken with a coefficient of 1.25: 2 590 000·1.25=3 327 500 rubles.

According to the normative cost of design work, the coefficient "α" will take a value equal to 8.06.

According to the methodology, in this case there are such complicating design factors as:

- Objects with the presence of explosive industries and zones, $K_i = 1{,}3$;
- Especially dangerous, technically complex objects, $K_i = 1{,}4$.

Then the product of the correction coefficients will be equal to:

$$PC_i = 1{,}3 \cdot 1{,}4 = 1{,}82$$

Now it is possible to calculate the cost of design work:

$$C_{pr(b)} = \frac{C_{con(b)} \cdot \alpha}{100} \cdot PC_i = \frac{76\,247\,000 \cdot 8{,}06}{100} \cdot 1{,}82 \approx 11\,185\,000\, rub.$$

Cost type	Cost, rub.
Equipment	73 837 000

Design work	11 185 000
Construction and installation works	2 590 000
Transportation fare	10 750 000
Commissioning works	1 130 000
Costs for equipment, tare and packaging	4 930 000
Procurement and storage costs	964 000
Training	586 000
Other costs	1 430 000
Total	107 402 000

Table 22: Capital costs

It is also necessary to take into account the operating costs associated with the operation of the system. Operating costs include many items, so the main factors will be discussed in detail. One part of the cost of maintaining and operating equipment is depreciation.

Depreciation is the process of compensation in cash for the depreciation of fixed assets by gradually transferring their value to newly created products in the production process. The amount of funds included in the cost of manufactured products, work performed, services rendered is called depreciation.

There are several ways to determine the amount of depreciation deductions:

- Linear;
- non-linear;
- Declining balance method;
- Write-off method based on the sum of years of use;
- Write-off method in proportion to manufactured products.

The work uses a linear method. Then the annual depreciation value is determined according to the formula:

$A_t = C_H \cdot H_a$ (8)

where:

C_H – initial cost of fixed assets (capital investments), rub.;

H_a – depreciation rate calculated by the formula:

$H_a = \frac{1}{T}$(9)

where:

T – equipment service life, years.

The turbo expander plant has the shortest service life in the system. On average, the resource of turboexpanders before overhaul is from 25 to 45 thousand hours (from 2.85 years to 5.14 years). We will take one overhaul of the installation for the time of the implementation of the object. The first year of the project implementation will be allocated for investment of capital expenditures and construction and installation works. The project implementation period will be 11 years (the first year is considered as zero when making calculations).

Since construction and installation work is carried out in the first year, the service life of the equipment is assumed to be 10 years, then the depreciation rate will be equal to:

$$H_a = \frac{1}{10} = 0{,}1$$

Now it is possible to calculate the annual depreciation rate:

$$A_t = 107\ 402\ 000 \cdot 0{,}1 = 10\ 740\ 200\ rub.$$

The table below shows approximate annual operating costs.:

Expenditure type	Cost, rub.
Wages of employees (including deductions to various funds)	878 000
Materials	4 120 000
Maintenance	10 967 000
Depreciation	10 740 000
Scheduled repairs	9 560 000

Emergency repairs	5 135 000
Fire safety	430 000
Occupational health and safety	546 000
Other costs	1 340 000
Total:	43 716 000

Table 33: Operating costs

Thus, the initial data were determined to assess the economic efficiency of the project:

Parameter	Value
Energy savings, rub./year	1 381 000
Volume of produced hydrogen, m^3/year	876 000
Price of hydrogen per 1 m^3, rub.	65
Capital costs, rub.	107 402 000
Operating costs, rub.	43 716 000
Total implementation period, years	11

Table 44: Initial data

4.2 Performance indicators

Net present value (NPV) is the amount of income reduced to the initial moment of the company's creation, which is expected after the return on invested capital and the receipt of an annual percentage equal to the discount rate chosen by the investor.

The discount rate is assumed to be 10%.

Net present value is calculated as the difference between the discounted cash inflows and outflows received by the company in the course of its operation.:

$$NPV = \sum_{t=0}^{T} \frac{IN_t}{(1+E_H)^t} - \sum_{t=1}^{T} \frac{Out_t}{(1+E_H)^t} \quad (10)$$

or

$$NPV = \sum_{t=0}^{T} \frac{S_t - C_t - O_{prt} - T_t + D_t}{(1+E_H)^t} \qquad (11)$$

where:

In_t – cash receipts in the time interval t, forming the input cash flow (inflow);

Out_t – cash payments in the time interval t, forming the output cash flow (outflow);

T – calculation duration;

E_H – discount rate adopted to evaluate the investment project;

S_t – sales revenue in year t;

C_t – capital investment in fixed assets in year t;

O_{prt} – operating costs (production, sales and management) in year t;

T_t – tax payments not included in production costs in year t;

D_t – depreciation charge in year t.

To make a decision on investing money in a company, it is necessary that the NPV be greater than 0.

The internal rate of return (IRR) is the value of the discount rate at which the net present value goes to zero.:

$$\sum_{t=0}^{T} \frac{In_t}{(1+IRR)^t} = \sum_{t=0}^{T} \frac{Out_t}{(1+IRR)^t} \qquad (12)$$

In the work, IRR is calculated in two ways:

- graphically;
- through the VSD function of the MS EXCEL program.

The discounted investment return index (ID) is the ratio of NPV to the accumulated discounted investment volume increased by one. If the value of the profitability index is greater than 1, then the project is considered economically viable.:

$$ID = 1 + \frac{NPV}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \qquad (13)$$

Второй вид формулы:

$$ID = \frac{\sum_{t=0}^{T} \frac{S_t - O_{prt} - T_t + D_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \qquad (14)$$

The discounted payback period (DPP) is the duration of the period from the initial moment to the earliest point in time in the billing period, after which the accumulated discounted cash flow becomes positive and then remains non-negative.

DPP can be determined by knowing the year T+ in which the company began to make a profit, taking into account capital investments. The payback period is calculated by the formula:

$$T_p = T^{+} - \frac{NPV(T^{+})}{NPV(T^{+}-1)} \quad (15)$$

where:

T^{+} – integer number of years of project payback, years.

It is advisable to present the payback period graphically, postponing on one axis the year of the company's operation, on the other, the accumulated discounted cash flow.

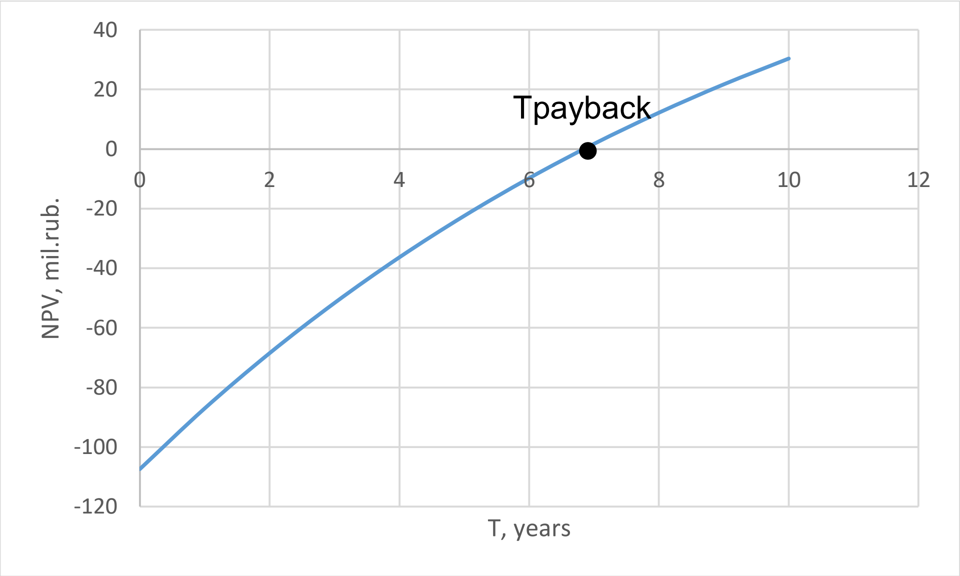


Figure 26: Payback period of the project

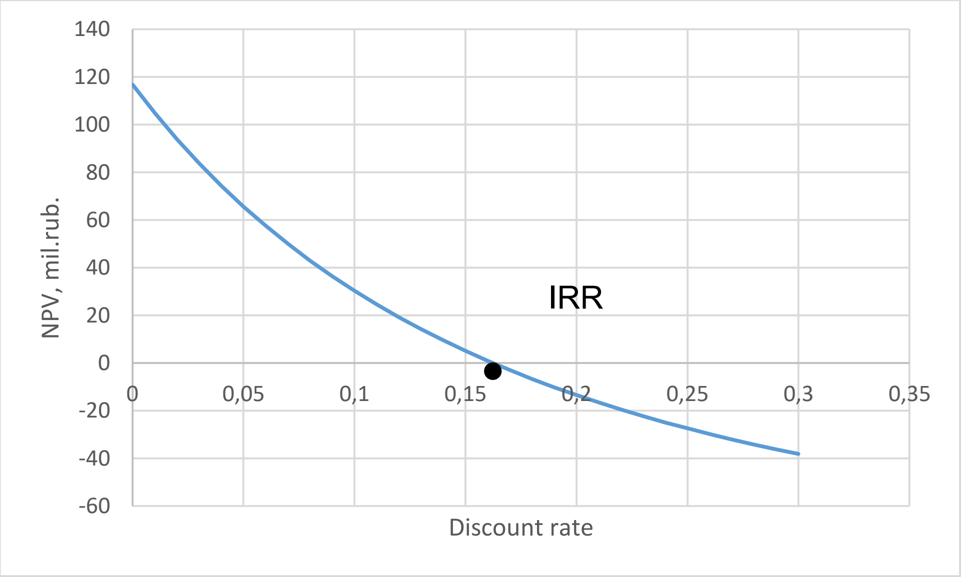


Figure 27: Internal rate of return

The table below shows the economic efficiency indicators of the project:

Index	Value
Net present value, million rubles	30,367
Internal rate of return, %	16,2
Discounted investment return index	1,28
Payback period, years	6,85

Table 55: Indicators of economic efficiency of the project

4.3 Risk assessment

The task of qualitative analysis is to identify certain types of risks and develop measures to minimize them. Table 7 presents a list of risks in the operation of the expander, the hydrogen production unit and the gas distribution point as a whole.

Type of risk	Risk mitigation measures
Leakage of hydrogen and the formation of an explosive mixture with oxygen	Installation of hydrogen concentration control sensors
Falling hydrogen prices	Conclusion of long-term agreements
Emergencies at work, accidents	Conducting briefings for personnel, monitoring the condition of the

	equipment used, conducting timely maintenance and repairs
Reduced gas transfer volumes and reduced hydrogen production	Use of more modern and energy efficient equipment
Failure of the automation system	System diagnostics, redundancy of control systems
Increase in capital and operating costs	Lending to cover additional costs

Table 66: Possible risks

For a quantitative risk analysis of a project, a sensitivity analysis is recommended. The following risks are usually considered during a sensitivity study:

- risk of changes in hydrogen production;
- risk of changes in hydrogen price;
- risk of changes in the required capital investments;
- risk of changes in operating cost.

There are two main methods of sensitivity analysis that do not contradict each other and therefore can be used both in combination and separately: the reference point method and the method of rational ranges or dependencies. The method of reference points was used in the work.

Reference point method. It is based on finding such a value of the indicator at which the resulting criterion (NPV) is equal to zero. The critical level of the indicator found in this way is compared with its predicted value. The smaller the discrepancy between the critical and predicted levels, the higher the sensitivity of the criterion in relation to this indicator, since the higher the probability of reaching the critical point.

Index	Expected value	Critical value (reference point)	Relative critical change, %
Rate of hydrogen production, m^3/year	876 000	781 000	-10,84

Operating costs, million rubles	43,716	49,894	14,13

Table 77: Results of RPM sensitivity analysis

As can be seen from the table, with a decrease in production volumes, NPV will fall, and a similar reaction will be with an increase in operating costs. If we compare the influence of the rate of hydrogen production and operating costs on NPV, then it follows from the analysis data that the hydrogen production rate factor has the highest sensitivity, since the relative critical change in modulus of this input parameter is less than that of operating costs.

5 Conclusion

A scheme of an expander-generator regulator is proposed for the purpose of recuperating the pressure energy lost during the reduction of gas pressure at gas distribution points. To confirm the operability of the system, a number of experiments were carried out with the creation of disturbances in the form of fluctuations in the withdrawal of gas by consumers and pressure at the inlet to the gas distribution point. The system showed stable operation in non-stationary conditions.

The possibility of utilizing the electricity produced by the expander-generator regulator for the production of hydrogen is considered. The calculation based on the data of the loading of gas distribution stations of PAO Gazprom in the Leningrad Region showed the feasibility of this approach, which was confirmed by further economic calculation. A technological scheme of the proposed electrolysis plant has been developed.

6 Bibliography

Abbott, D./Bowers, J. (2014): The impact of natural gas composition variations on the operation of gas turbines for power generation.

Abdalla, Abdalla M./Hossain, Shahzad/Nisfindy, Ozzan B./Azad, Atia T./Dawood, Mohamed/Azad, Abul K. (2018): Hydrogen production, storage, transportation and key challenges with applications: A review. In: Energy Conversion and Management, 165, 602–627.

Abdin, Zainul/Zafaranloo, Ali/Rafiee, Ahmad/Mérida, Walter/Lipiński, Wojciech/Khalilpour, Kaveh R. (2020): Hydrogen as an energy vector. In: Renewable and Sustainable Energy Reviews, 120, 109620.

Abe, J.O./Popoola, A.P.I./Ajenifuja, E./Popoola, O.M. (2019): Hydrogen energy, economy and storage: Review and recommendation. In: International Journal of Hydrogen Energy, 44 (29), 15072–15086.

Acar, Canan/Dincer, Ibrahim (2019): Review and evaluation of hydrogen production options for better environment. In: Journal of Cleaner Production, 218, 835–849.

Adolf, Jörg/Balzer, Christoph/Louis, Jurgen/Schabla, Uwe/Fischedick, Manfred/Arnold, Karin/Pastowski, Andreas/Schüwer, Dietmar (2017): Shell Hydrogen Study Energy of the Future? Sustainable Mobility through Fuel Cells and H2.

Aksenov, D.T., Aksenova, G.P. (2009): A Method for Sustainable Gas Supply by a Gas Distribution Station with an Energy Refrigeration Complex Using Overpressure Energy of Natural Gas to Generate Electricity and Cold, and a System for Implementing the Method. Patent RF 2346205. Patent RF 2346205.

Andersson, J./Grönkvist, S. (2019): Large-scale storage of hydrogen. In: International Journal of Hydrogen Energy, 44 (23), 11901–11919.

Arabkoohsar, A./Farzaneh-Gord, M./Deymi-Dashtebayaz, M./Machado, L./Koury, R.N.N. (2015): A new design for natural gas pressure reduction points by employing a turbo expander and a solar heating set. In: Renewable Energy, 81, 239–250.

Arabkoohsar, A./Machado, L./Koury, R.N.N. (2016): Operation analysis of a photovoltaic plant integrated with a compressed air energy storage system and a city gate station. In: Energy, 98, 78–91.

Arshinov, M.S. (2012): Calculation and analysis of seasonal irregularity in the operation of gas gathering systems of the polar field for 2007-2009. and for the future.

Atilhan, S./Park, S./El-Halwagi, M.M./Atilhan, M./Moore, M./Nielsen, R.B. (2021): Green hydrogen as an alternative fuel for the shipping industry. In: Current Opinion in Chemical Engineering, 31.

Badami, Marco/Modica, Stefano/Portoraro, Armando (2017): A biofuel-based cogeneration plant in a natural gas expansion system: An energetic and economic assessment. In: Applied Thermal Engineering, 118, 52–61.

Barbarelli, S./Florio, G./Scornaienchi, N.M. (2018): Developing of a small power turbine recovering energy from low enthalpy steams or waste gases: Design, building and experimental measurements. In: Thermal Science and Engineering Progress, 6, 346–354.

Bareiß, Kay/de la Rua, Cristina/Möckl, Maximilian/Hamacher, Thomas (2019): Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. In: Applied Energy, 237, 862–872.

Bartela, Łukasz/Katla, Daria/Skorek-Osikowska, Anna (2021): Evaluation of conceptual electrolysis-based energy storage systems using gas expanders. In: International Journal of Hydrogen Energy, International Journal of Hydrogen Energy Special Issue devoted to the 32nd International Conference ECOS 2019, 46 (38), 20171–20182.

Baykara, Sema Z. (2018): Hydrogen: A brief overview on its sources, production and environmental impact. In: International Journal of Hydrogen Energy, The 2nd International Hydrogen Technologies Congress (IHTEC-2017), 43 (23), 10605–10614.

Belousov, A.E./Kabanov, O.V. (2017): Expander-generator unit with its control system. Patent RU2620624C1.

Belousov, Artem Evgenevich/Ovchinnikov, Egor Sergeevich (2022): Mathematical Modeling of the Operation of an Expander-Generator Pressure Regulator in Non-Stationary Conditions of Small Gas Pressure Reduction Stations. In: Mathematics, 10 (3), 393.

Borelli, Davide/Devia, Francesco/Lo Cascio, Ermanno/Schenone, Corrado (2018): Energy recovery from natural gas pressure reduction stations: Integration with low temperature heat sources. In: Energy Conversion and Management, 159, 274–283.

Buttler, Alexander/Spliethoff, Hartmut (2018): Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. In: Renewable and Sustainable Energy Reviews, 82, 2440–2454.

Cao, C./Liao, J./Hou, Z./Xu, H./Mehmood, F./Wu, X. (2020): Utilization of CO2 as cushion gas for depleted gas reservoir transformed gas storage reservoir. In: Energies, 13 (3).

Capurso, T./Stefanizzi, M./Torresi, M./Camporeale, S.M. (2022): Perspective of the role of hydrogen in the 21st century energy transition. In: Energy Conversion and Management, 251.

Chaudhry, Mohammed Muslim (2015): Method of Producing Hydrogen Gas from Water. US20150329978A1.

Danieli, Piero/Carraro, Gianluca/Lazzaretto, Andrea (2020): Thermodynamic and Economic Feasibility of Energy Recovery from Pressure Reduction Stations in Natural Gas Distribution Networks. In: Energies, 13 (17), 4453.

David, Martín/Ocampo-Martínez, Carlos/Sánchez-Peña, Ricardo (2019): Advances in alkaline water electrolyzers: A review. In: Journal of Energy Storage, 23, 392–403.

Davidson, Nehemia (2012): Power Generator Utilizing Circulated Working Fluid from a Pulsed Electrolysis System and Method of Using Same. US20120104766A1.

Davis, Jonathan T./Qi, Ji/Fan, Xinran/Bui, Justin C./Esposito, Daniel V. (2018): Floating membraneless PV-electrolyzer based on buoyancy-driven product separation. In: International Journal of Hydrogen Energy, 43 (3), 1224–1238.

Dawood, Furat/Anda, Martin/Shafiullah, G.M. (2020): Hydrogen production for energy: An overview. In: International Journal of Hydrogen Energy, 45 (7), 3847–3869.

Demir, Murat Emre/Dincer, Ibrahim (2018): Cost assessment and evaluation of various hydrogen delivery scenarios. In: International Journal of Hydrogen Energy, 43 (22), 10420–10430.

Diao, Anna/Wang, Yuli/Guo, Yi/Feng, Mingzhi (2018): Development and application of screw expander in natural gas pressure energy recovery at city gas station. In: Applied Thermal Engineering, 142, 665–673.

Dvoynikov, M./Buslaev, G./Kunshin, A./Sidorov, D./Kraslawski, A./Budovskaya, M. (2021): New concepts of hydrogen production and storage in Arctic region. In: Resources, 10 (1), 1–18.

El-Emam, Rami S./Özcan, Hasan (2019): Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. In: Journal of Cleaner Production, 220, 593–609.

El-Halwagi, Mahmoud/Sengupta, Debalina/Pistikopoulos, Efstratios/Sammons, Jeffrey/Eljak, Fadwa/Kazi, Monzure-Khoda (2020): Disaster-Resilient Design of Manufacturing Facilities Through Process Integration: Principal Strategies, Perspectives, and Research Challenges. In: Frontiers in Sustainability, 1.

Farzaneh-Gord, Mahmood/Ghezelbash, Reza/Sadi, Meisam/Moghadam, Ali Jabari (2016): Integration of vertical ground-coupled heat pump into a conventional natural gas pressure drop station: Energy, economic and CO2 emission assessment. In: Energy, 112, 998–1014.

Farzaneh-Gord, Mahmood/Hashemi, Shahram/Sadi, Meisam (2007): Energy Destruction in Iran’s Natural Gas Pipe Line Network. In: Energy Exploration & Exploitation, 25 (6), 393–406.

Farzaneh-Gord, M./Sadi, M. (2008): Enhancing energy output in Iran’s natural gas pressure drop stations by cogeneration. In: Journal of the Energy Institute, 81 (4), 191–196.

Fetisov, V./Shalygin, A.V./Modestova, S.A./Tyan, V.K./Shao, C. (2023): Development of a Numerical Method for Calculating a Gas Supply System during a Period of Change in Thermal Loads. In: Energies, 16 (1).

FM.C Silly sur Nied/Pluvinage, Guy/Capelle, J., LEM3 Université de Lorraine (2019): Design and maintenance of pipe networks transporting hydrogen pure or blended with natural gas. In: Pipeline Science and Technology, 3 (1), 30–45.

Fokin G.A. (2015): Methodology for the Creation of Autonomous Turbine Sources of Electrical Energy Using the Energy of Compressed Natural Gas for the Own Needs of the Gas Transmission System of Russia. St. Petersburg, Russia: Peter the Great St. Petersburg Polytechnic University.

Gabrielli, P./Poluzzi, A./Kramer, G.J./Spiers, C./Mazzotti, M./Gazzani, M. (2020): Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. In: Renewable and Sustainable Energy Reviews, 121.

Garanin, Oleg Evgenievich/Dubrov, Yuri Vladimirovich/Gorelova, Svetlana Alekseevna/Ilyichev, Sergey Vladimirovich/Khabibullin, Alexander Maratovich (2012): Forecasting and control of gas consumption of socially significant subscribers. In: Russian gas, (2).

Gataullina, A.R./Baykov, I.R./Molchanova, R.A./Kulagina, O.V. (2013): Use of pressure energy of transported natural gas. In: Transport and storage of petroleum products and hydrocarbons, (2), 37–39.

„Gazprom“, Russian joint-stock company (2017): Categorization of electrical receivers of industrial facilities of PJSC Gazprom. Документы нормативные для проектирования, строительства и эксплуатации объектов ПАО „Газпром“.

Ghaebi, Hadi/Farhang, Behzad/Rostamzadeh, Hadi/Parikhani, Towhid (2018): Energy, exergy, economic and environmental (4E) analysis of using city gate station (CGS) heater waste for power and hydrogen production: A comparative study. In: International Journal of Hydrogen Energy, 43 (3), 1855–1874.

Glenk, Gunther/Reichelstein, Stefan (2019): Economics of converting renewable power to hydrogen. In: Nature Energy, 4 (3), 216–222.

Golyanov, Andrey Ivanovich (2008): Gas networks and gas storage facilities: a textbook for university students and students of in-t. prof. education students in the specialty 130500 „Design, construction and operation of gas and oil pipelines and gas and oil storage facilities“. 2nd ed., revised. and additional. Ufa: Monograph.

GOST 5541-2014 (2014): Interstate standard GOST 5542-2014 „Combustible natural gases for industrial and domestic purposes. Specifications“.

Gutiérrez-Martín, F./Amodio, Lidia/Pagano, Maurizio (2021): Hydrogen production by water electrolysis and off-grid solar PV. In: International Journal of Hydrogen Energy, HYDROGEN ENERGY SYSTEMS, 46 (57), 29038–29048.

Haeseldonckx, Dries/D’haeseleer, William (2007): The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure. In: International Journal of Hydrogen Energy, EHEC2005, 32 (10), 1381–1386.

Han, W.B./Kim, I.S./Kim, M./Cho, W.C./Kim, S.K./Joo, J.H./Lee, Y.W./Cho, Y./Cho, H.S./Kim, C.H. (2021): Directly sputtered nickel electrodes for alkaline water electrolysis. In: Electrochimica Acta, 386.

Hassan, I.A./Ramadan, H.S./Saleh, M.A./Hissel, D. (2021): Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives. In: Renewable and Sustainable Energy Reviews, 149.

Hassanpouryouzband, A./Joonaki, E./Edlmann, K./Haszeldine, R.S. (2021): Offshore Geological Storage of Hydrogen: Is This Our Best Option to Achieve Net-Zero? In: ACS Energy Letters, 6, 2181–2186.

He, T.B./Ju, Y.L. (2013): Design and optimization of natural gas liquefaction process by utilizing gas pipeline pressure energy. In: Applied Thermal Engineering, 57 (1), 1–6.

Heinemann, N./Alcalde, J./Miocic, J.M./Hangx, S.J.T./Kallmeyer, J./Ostertag-Henning, C./Hassanpouryouzband, A./Thaysen, E.M./Strobel, G.J./Schmidt-Hattenberger, C./Edlmann, K./Wilkinson, M./Bentham, M./Stuart Haszeldine, R./Carbonell, R./Rudloff, A. (2021): Enabling large-scale hydrogen storage in porous media-the scientific challenges. In: Energy and Environmental Science, 14 (2), 853–864.

Hirscher, Michael/Yartys, Volodymyr A./Baricco, Marcello/Bellosta von Colbe, Jose/Blanchard, Didier/Bowman, Robert C./Broom, Darren P./Buckley, Craig E./Chang, Fei/Chen, Ping/Cho, Young Whan/Crivello, Jean-Claude/Cuevas, Fermin/David, William I.F./de Jongh, Petra E./Denys, Roman V./Dornheim, Martin/Felderhoff, Michael/Filinchuk, Yaroslav/Froudakis, George E./Grant, David M./Gray, Evan MacA./Hauback, Bjørn C./He, Teng/Humphries, Terry D./Jensen, Torben R./Kim, Sangryun/Kojima, Yoshitsugu/Latroche, Michel/Li, Hai-Wen/Lototskyy, Mykhaylo V./Makepeace, Joshua W./Møller, Kasper T./Naheed, Lubna/Ngene, Peter/Noréus, Dag/Nygård, Magnus Moe/Orimo, Shin-ichi/Paskevicius, Mark/Pasquini, Luca/Ravnsbæk, Dorthe B./Veronica Sofianos, M./Udovic, Terrence J./Vegge, Tejs/Walker, Gavin S./Webb, Colin J./Weidenthaler, Claudia/Zlotea, Claudia (2020): Materials for hydrogen-based energy storage – past, recent progress and future outlook. In: Journal of Alloys and Compounds, 827, 153548.

Hossain, M.J./Pota, H.R./Ramos, R.A. (2011): Robust STATCOM control for the stabilisation of fixed-speed wind turbines during low voltages. In: Renewable Energy, 36 (11), 2897–2905.

Hota, P./Das, A./Maiti, D.K. (2023): A short review on generation of green fuel hydrogen through water splitting. In: International Journal of Hydrogen Energy, 48 (2), 523–541.

Joint Stock Company Gazprom Gas Distribution (2023).

Jorschick, H./Preuster, P./Bösmann, A./Wasserscheid, P. (2021): Hydrogenation of aromatic and heteroaromatic compounds-a key process for future logistics of green hydrogen using liquid organic hydrogen carrier systems. In: Sustainable Energy and Fuels, 5 (5), 1311–1346.

Karasevich, V.A./Chernykh, A.S./Yakovlev, A.A. (2016): Prospects for the use of autonomous energy sources in the transportation and distribution of gas. In: Scientific Journal of the Russian Gas Society, (1).

Kargaran, Mahyar/Arabkoohsar, A./Hagighat-Hosini, S.J./Farzaneh-Kord, V./Farzaneh-Gord, Mahmood (2013): The second law analysis of natural gas behavior within a vortex tube. In: Thermal Science, 17 (4), 1079–1092.

Khan, Muhammad Arif/Zhao, Hongbin/Zou, Wenwen/Chen, Zhe/Cao, Wenjuan/Fang, Jianhui/Xu, Jiaqiang/Zhang, Lei/Zhang, Jiujun (2018): Recent Progresses in Electrocatalysts for Water Electrolysis. In: Electrochemical Energy Reviews, 1 (4), 483–530.

Kojima, Hirokazu/Matsumoto, Hideyuki/Tsujimura, Taku (2017): Development of large scale unified system for hydrogen energy carrier production and utilization: Experimental analysis and systems modeling. In: International Journal of Hydrogen Energy, Special Issue on The 21st World Hydrogen Energy Conference (WHEC 2016), 13-16 June 2016, Zaragoza, Spain, 42 (19), 13444–13453.

Kostowski, Wojciech (2010): The Possibility of Energy Generation within the Conventional Natural Gas Transport System. In: Strojarstvo, 52, 429–440.

Kostowski, Wojciech J./Usón, Sergio (2013): Comparative evaluation of a natural gas expansion plant integrated with an IC engine and an organic Rankine cycle. In: Energy Conversion and Management, 75, 509–516.

Kuczyński, Szymon/Łaciak, Mariusz/Olijnyk, Andrzej/Szurlej, Adam/Włodek, Tomasz (2019): Techno-Economic Assessment of Turboexpander Application at Natural Gas Regulation Stations. In: Energies, 12 (4), 755.

Kumar, A./Singh, A. (2023): An Overview Modeling Approach for Spontaneous Condensation Flow of Cryogenic Turboexpander. In: Lecture Notes in Mechanical Engineering, 443–455.

Kumar, M./Biswal, R./Behera, S.K./Sahoo, R.K./Pal, S. (2022): Experimental and numerical approach for characterization and performance evaluation of cryogenic turboexpander under rotating condition. In: International Communications in Heat and Mass Transfer, 136.

Leusheva, E.L./Morenov, V.A. (2017): Development of combined heat and power system with binary cycle for oil and gas enterprises power supply. In: Neftyanoe khozyaystvo - Oil Industry, (7), 104–106.

LIU, Weijia/WEN, Fushuan/XUE, Yusheng (2017): Power-to-gas technology in energy systems: current status and prospects of potential operation strategies. In: Journal of Modern Power Systems and Clean Energy, 5 (3), 439–450.

Lord, Anna S./Kobos, Peter H./Borns, David J. (2014): Geologic storage of hydrogen: Scaling up to meet city transportation demands. In: International Journal of Hydrogen Energy, 39 (28), 15570–15582.

Lord, A.S./Kobos, P.H./Borns, D.J. (2014): Geologic storage of hydrogen: Scaling up to meet city transportation demands. In: International Journal of Hydrogen Energy, 39 (28), 15570–15582.

Matos, C.R./Carneiro, J.F./Silva, P.P. (2019): Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. In: Journal of Energy Storage, 21, 241–258.

Mazumder, M./Xu, Q./Nath, F. (2023): Thermodynamic-Certified Conceptual Design of a DMR Refrigeration System for the Natural Gas Liquefaction Process. In: Industrial and Engineering Chemistry Research, 62 (4), 1916–1926.

McCambridge, Michael (1988): Electrolysis of water. US4726888A.

Melaina, Marc/Sozinova, Olga/Penev, Michael (2013): Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues.

Meng, Y./Zhang, Y./Wang, J./Chen, S./Hou, Y./Chen, L. (2023): Performance optimization of turboexpander-compressors for energy recovery in small air-separation plants. In: Energy, 271.

Milani, D./Kiani, A./McNaughton, R. (2020): Renewable-powered hydrogen economy from Australia’s perspective. In: International Journal of Hydrogen Energy, 45 (46), 24125–24145.

Mohod, Sharad W./Aware, Mohan V. (2010): A STATCOM-Control Scheme for Grid Connected Wind Energy System for Power Quality Improvement. In: IEEE Systems Journal, 4 (3), 346–352.

Moreno-Blanco, J./Petitpas, G./Espinosa-Loza, F./Elizalde-Blancas, F./Martinez-Frias, J./Aceves, S.M. (2019): The storage performance of automotive cryo-compressed hydrogen vessels. In: International Journal of Hydrogen Energy, 44 (31), 16841–16851.

Mouli-Castillo, J./Heinemann, N./Edlmann, K. (2021): Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study. In: Applied Energy, 283.

Neseli, Mehmet Alparslan/Ozgener, Onder/Ozgener, Leyla (2015): Energy and exergy analysis of electricity generation from natural gas pressure reducing stations. In: Energy Conversion and Management, 93, 109–120.

Ogden, Joan/Jaffe, Amy Myers/Scheitrum, Daniel/McDonald, Zane/Miller, Marshall (2018): Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature. In: Energy Policy, 115, 317–329.

Osman, A.I./Deka, T.J./Baruah, D.C./Rooney, D.W. (2020): Critical challenges in biohydrogen production processes from the organic feedstocks. In: Biomass Conversion and Biorefinery.

Osman, A.I./Mehta, N./Elgarahy, A.M./Hefny, M./Al-Hinai, A./Al-Muhtaseb, A.H./Rooney, D.W. (2022): Hydrogen production, storage, utilisation and environmental impacts: a review. In: Environmental Chemistry Letters, 20 (1), 153–188.

Panarin, M.V./Pakhomov, S.N./Vorobiev, N.Y., Tsarkov, G.Y. (2016): Turbine Expander Control Device. Patent RF 2579301. Patent RF 2579301.

Parra, David/Valverde, Luis/Pino, F. Javier/Patel, Martin K. (2019): A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. In: Renewable and Sustainable Energy Reviews, 101, 279–294.

Perry, K.F. (2005): Natural Gas Storage Industry Experience and Technology: Potential Application to CO2 Geological Storage. In: Carbon Dioxide Capture for Storage in Deep Geologic Formations. 815–825.

Pozivil, Jaroslav (2004): Use of Expansion Turbines in Natural Gas Pressure Reduction Stations. In: Acta Montanistica Slovaca, 9.

Rahm, Steve/Goldmeer, Jeffrey/Molière, Michel/Eranki, Aditya (2009): Addressing gas turbine fuel flexibility. In: GER4601, General Electric.

Rahman, Mohammed Mahbubur (2010): Power generation from pressure reduction. In: Journal of Mechanical Engineering, 41 (2), 89–95.

Rastegar, Saeed/Kargarsharifabad, Hadi/Shafii, Mohammad Behshad/Rahbar, Nader (2020): Experimental investigation of the increasing thermal efficiency of an indirect water bath heater by use of thermosyphon heat pipe. In: Thermal Science, 24 (6 Part B), 4277–4287.

Reuß, Markus/Welder, Lara/Thürauf, Johannes/Linßen, Jochen/Grube, Thomas/Schewe, Lars/Schmidt, Martin/Stolten, Detlef/Robinius, Martin (2019): Modeling hydrogen networks for future energy systems: A comparison of linear and nonlinear approaches. In: International Journal of Hydrogen Energy, 44 (60), 32136–32150.

Saba, Sayed M./Müller, Martin/Robinius, Martin/Stolten, Detlef (2018): The investment costs of electrolysis – A comparison of cost studies from the past 30 years. In: International Journal of Hydrogen Energy, 43 (3), 1209–1223.

Safari, F./Dincer, I. (2020): A review and comparative evaluation of thermochemical water splitting cycles for hydrogen production. In: Energy Conversion and Management, 205.

Schipachev, Andrei M./Dmitrieva, Alena S. (2021): Application of the resonant energy separation effect at natural gas reduction points in order to improve the energy efficiency of the gas distribution system. In: Journal of Mining Institute, 248, 253–259.

Seo, Seung-Kwon/Yun, Dong-Yeol/Lee, Chul-Jin (2020): Design and optimization of a hydrogen supply chain using a centralized storage model. In: Applied Energy, 262, 114452.

Sheikhnejad, Yahya/Simões, João/Martins, Nelson (2020): Energy Harvesting by a Novel Substitution for Expansion Valves: Special Focus on City Gate Stations of High-Pressure Natural Gas Pipelines. In: Energies, 13 (4), 956.

Shiva Kumar, S./Himabindu, V. (2019): Hydrogen production by PEM water electrolysis – A review. In: Materials Science for Energy Technologies, 2 (3), 442–454.

Simanullang, M./Prost, L. (2022): Nanomaterials for on-board solid-state hydrogen storage applications. In: International Journal of Hydrogen Energy, 47 (69), 29808–29846.

Sokovnin, O.M./Zagoskina, N.V./Zagoskin, S.N. (2022): Thermodynamic calculation of the natural gas pressure reduction in a turboexpander. In: Journal of Applied Mechanics and Technical Physics, 63 (1), 89–95.

Staffell, Iain/Scamman, Daniel/Abad, Anthony Velazquez/Balcombe, Paul/Dodds, Paul E./Ekins, Paul/Shah, Nilay/Ward, Kate R. (2019): The role of hydrogen and fuel cells in the global energy system. In: Energy & Environmental Science, 12 (2), 463–491.

Stepanets, A.A. (1999): Evaluation of the effectiveness of the influence of expander-generator units on the operation of CHP. In: Thermal power engineering, (12).

Sun, H./Xu, X./Kim, H./Jung, W./Zhou, W./Shao, Z. (2023): Electrochemical Water Splitting: Bridging the Gaps between Fundamental Research and Industrial Applications. In: Energy and Environmental Materials.

Suslov, D...Y. (2015): Determination of the maximum hourly gas consumption. Belgorod: Издательствово БГТУ.

Taheri Seresht, Ramin/Khodaei Jalalabadi, Hassan/Rashidian, Babak (2010): Retrofit of Tehran City Gate Station (C.G.S.No.2) by Using Turboexpander. Paper präsentiert bei der ASME 2010 Power Conference, American Society of Mechanical Engineers Digital Collection, 207–212.

Taleshian, Mehdi/Rastegar, Hasan/Abyaneh, Hossein Askarian (2012): Modeling and Power Quality Improvement of Grid Connected Induction Generators Driven by Turbo-Expanders. In: International Journal of Energy Engineering, 2 (4), 131–137.

Tarkowski, R. (2019): Underground hydrogen storage: Characteristics and prospects. In: Renewable and Sustainable Energy Reviews, 105, 86–94.

Thema, M./Bauer, F./Sterner, M. (2019): Power-to-Gas: Electrolysis and methanation status review. In: Renewable and Sustainable Energy Reviews, 112, 775–787.

Turbodetanders (2023): Turbodetanders, Official website of NPP Gazelektropribor LLC.

Witkowski, Andrzej/Rusin, Andrzej/Majkut, Mirosław/Stolecka, Katarzyna (2018): Analysis of compression and transport of the methane/hydrogen mixture in existing natural gas pipelines. In: International Journal of Pressure Vessels and Piping, 166, 24–34.

Wulf, Christina/Reuß, Markus/Grube, Thomas/Zapp, Petra/Robinius, Martin/Hake, Jürgen-Friedrich/Stolten, Detlef (2018): Life Cycle Assessment of hydrogen transport and distribution options. In: Journal of Cleaner Production, 199, 431–443.

Xiong, Yaxuan/An, Shuo/Xu, Peng/Ding, Yulong/Li, Chuan/Zhang, Qunli/Chen, Hongbing (2018): A novel expander-depending natural gas pressure regulation configuration: Performance analysis. In: Applied Energy, 220, 21–35.

Yanxing, Z./Maoqiong, G./Yuan, Z./Xueqiang, D./Jun, S. (2019): Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen. In: International Journal of Hydrogen Energy, 44 (31), 16833–16840.

Yu, L./Zhu, Q./Song, S./McElhenny, B./Wang, D./Wu, C./Qin, Z./Bao, J./Yu, Y./Chen, S./Ren, Z. (2019): Non-noble metal-nitride based electrocatalysts for high-performance alkaline seawater electrolysis. In: Nature Communications, 10 (1).

Yue, Meiling/Lambert, Hugo/Pahon, Elodie/Roche, Robin/Jemei, Samir/Hissel, Daniel (2021): Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. In: Renewable and Sustainable Energy Reviews, 146, 111180.

Zamyatin, Egor/Voytyuk, Irina/Zamyatina, Elena (2019): Increasing the energy efficiency of an enterprise by point compensating of power quality distortions. In: E3S Web of Conferences, 140, 04010.

Zarnitsky, Georgy Emmanuilovich (1968): Theoretical foundations for the use of natural gas pressure energy. Текст. Moscow: Nedra.

Zhu, C./Liu, C./Fu, Y./Gao, J./Huang, H./Liu, Y./Kang, Z. (2019): Construction of CDs/CdS photocatalysts for stable and efficient hydrogen production in water and seawater. In: Applied Catalysis B: Environmental, 242, 178–185.

7 List of Figures

8 List of Tables

List of Abbreviations

GRP	Gas reduction point
GDS	Gas distribution station
EGU	Expander-generator unit
EGR	Expander generator regulator
NPV	Net present value
IRR	Internal rate of return
ID	Discounted investment return index
DPP	Discounted payback period
RPM	Reference point method

Annex

Year	Investments	Depreciation	Operating cost	Revenue	Profit	Net profit	Cash flow	NPV	Total NPV
2023	107,420	0	0	0	0	0	-107,420	-107,420	-107,420
2024	0	10,740	43,716	58,321	14,605	11,684	22,424	20,385	-87,034
2025	0	10,740	43,716	58,321	14,605	11,684	22,424	18,532	-68,501
2026	0	10,740	43,716	58,321	14,605	11,684	22,424	16,847	-51,654
2027	0	10,740	43,716	58,321	14,605	11,684	22,424	15,316	-36,338
2028	0	10,740	43,716	58,321	14,605	11,684	22,424	13,923	-22,414
2029	0	10,740	43,716	58,321	14,605	11,684	22,424	12,657	-9,756
2030	0	10,740	43,716	58,321	14,605	11,684	22,424	11,507	1,750
2031	0	10,740	43,716	58,321	14,605	11,684	22,424	10,461	12,211
2032	0	10,740	43,716	58,321	14,605	11,684	22,424	9,510	21,721
2033	0	10,740	43,716	58,321	14,605	11,684	22,424	8,645	30,367

Table 88: Calculations for determining performance indicators in million rubles