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NATIONAL ENERGY AND CLIMATE PLANS: IMPORTANCE OF SYNERGY

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In the modern world, including the European Union, the Baltic States and Latvia, the power industry has a broad definition, area and content, several social life and economic existence, comfort and safety provision. It also covers the following segments: heat/thermal energy, transport/fuel, electricity, energy resources and their types, etc.

More competent and wider synergy among different energy sectors and power industry and other areas provides the option to solve the global problems, for example, the mitigation of climate changes and the provision of energy sustainability by reducing the production of greenhouse gases, increasing the use of renewable energy sources, achieving higher energy efficiency and providing the careful use of energy resources. The results of synergy are of economic importance; they provide the efficiency and competitiveness of costs.

In this paper, the necessity of synergy between renewables and conventional generation and synergy among energy sectors are considered to achieve the dimensions of national energy and climate plans.

Keywords: *energy, infrastructure, national energy and climate plans, synergy*

1. INTRODUCTION

People’s existence is based on various forms and sources of energy, e.g., for lighting, heating, and transporting. In everyday life, various energy sources power devices. Fulfilling these objectives requires wiser energy use and effective socio-political measures to formulate rational national energy mix.

As outlined in Eurelectric Industry Vision, the energy system will be transformed to make it more responsive, resilient and efficient. It will be required to invest in clean power generation and transition-enabling solutions in order to reduce emissions and actively pursue efforts to become carbon-neutral before mid-century, taking into account different starting points and commercial availability of the main transition technologies. The key enablers are needed to achieve these ambitions [1].

The National Energy and Climate Plans are a key tool of the Energy Union Governance towards achieving the EU's 2030 *climate and energy* targets [2]: 1) at least 40 % cuts in greenhouse emissions; 2) at least 32 % share for renewable energy; 3) at least 32.5 % improvement in energy efficiency.

National Energy and Climate Plans (NECPs) cover the five dimensions of the energy union for the period of 2021 to 2030 [3]: 1) **energy security**, which implies the reduction of energy dependence and energy import, diversification of energy suppliers, the increase of energy system flexibility; 2) **internal energy market**, which includes the expansion of power infrastructure (interconnections), the expansion and provision of energy transmission infrastructure; the provision of internal energy market operation; the decrease of energy poverty; 3) **energy efficiency** – the reduction of primary energy sources use, the reduction of energy use in final gross energy consumption; the improvements of building efficiency; the long-term strategy of building renovation; 4) **decarbonisation** of the economy – greenhouse gas reduction; renewables increase and CO_2 capture increase; 5) **research, innovation and competitiveness** – private and public research, the promotion of clean energy technologies, the improvement of competitiveness.

The achievement of NECP dimensions is going to bring new trends in power sectors, thus resulting in challenges related to electric utilities and the necessity of their response to these challenges, for example:

- *Decarbonisation and electrification:* in the latest study of *Eurelectric* "Decarbonisation Pathways" [4], it has been marked that decarbonisation is possible only through the wide electrification of the transport, heating and cooling sectors. We see a great progress in creation of charging infrastructure for electric vehicles in the Baltic States, but unfortunately there is a lack of coordination among different operators, payment systems and standards. The number of electric vehicles is still far below the necessary critical mass to make this business profitable. The most promising technologies in electric heating and cooling are heat pumps and chillers, which use latent heat from the environment. In combination with renewable resources, these are one of the greatest possibilities for reduction of primary energy consumption.
- *Power system integration and synchronisation:* for instance, the most important project for the power sector of the Baltic States is power system integration (synchronization) with the European Continental Network. It is not only political, but also technical challenge. Implementation of the synchronous connection with only one double circuit high-voltage alternating current (HVAC) line and one submarine high-voltage direct current (HVDC) cable potentially has a high risk of bringing the Baltic power systems into the state of island operation. With reduction of domestic generation capacity, it could be a quite worrying signal for security of electricity supply. Another challenge is the necessity to deliver ancillary services, such as primary frequency control (FCR – frequency

containment reserve) and inertia, which before synchronisation are mostly provided by the Russian power system. Baltic power transmission system operators are trying to solve this problem independently, rather than creating a solid trading platform for ancillary services. Battery electric storage system could be used for multiple applications, including provision of ancillary services and enhancing performance of power plants. That is why Latvenergo Group is considering it as an option for one of its combined cycle gas turbine (CCGT) plants (Riga TPP-1).

- *Sector coupling and energy storage solutions:* Sector coupling is another industry trend to be seriously considered. It means energy conversion from one energy source to the other and very often with the purpose of energy storage. P2G (power-to-gas, such as hydrogen) and P2F (power-to-fuels, such as methanol) generation have great prospective in the future. It could allow for much greater energy storage volumes than in heat storage facilities.
- *Synergy from market liberalization and integration:* Synergetic effect could be expected from market coupling. In the early 90s, restructuring and liberalization of electricity markets started, followed by gas market deregulation. Nowadays more efforts are spent for enabling competition in district heating markets. In large district heating systems (DHS), it becomes possible and feasible. Likewise in electricity and gas markets, competition in the district heating will take place not only in wholesale (among heat producers), but also in retail (among heat suppliers) segments. With evolution of the 4th generation DHS, also households and small enterprises will have an opportunity to feed their produced heat into the district heating network. For the utility, it is important to have a planning tool to optimize its operations in all three closely linked markets.
- *Data management:* rollout of smart meters and data management systems allow customers to obtain their load profiles, remotely disconnect their property from power supply, install microgeneration (such as solar panels) and make use of bidirectional power flows to benefit from net accounting system advantages. Digitalisation in the power sector will allow automating different technological processes and inventing different control and monitoring systems, which will continuously evaluate the equipment and provide recommendations for its maintenance. Smart meters also allow customers to receive dynamic pricing products from their electricity suppliers.
- *Smart cities and technologies:* future vision of smart houses assumes not only smart sensors (temperature, humidity, CO_2), circuits (switching devices), regulators (heating & cooling, lighting, shading), but also control of heat and electricity production for domestic use, as well as charging of electric vehicles.
- Future design of a power system may face transformation from centralized to more deregulated. Some customers or communities may have a wish to create their own microgrids.

In this paper, the dimension "decarbonisation" is considered in detail. This dimension is developing very rapidly. For example, today, the five countries that comprise the Nordic region – Denmark, Finland, Iceland, Norway, and Sweden – have progressive energy and climate policies that are perhaps the most ambitious in the world. Each is attempting to become entirely or mostly "fossil fuel free" or "carbon neutral" with Denmark, Sweden, and Norway committed to 100 % renewable energy penetration, Finland 80 %, and Iceland 50 %–75 % [5].

Figures 1 and 2 reflect the forecast of Nordic electricity and heat production from 2013 to 2050 according to Carbon-Neutral Scenario (CNS) [6]. This scenario is developed taking into account the local abundant wind resources together with already existing dispatchable hydropower. Mainly wind and slightly solar power will displace the fossil and nuclear in electricity generation. In heat production, electricity is going to dominate, thus adding flexibility to an integrated power and heat system and phasing-out of oil-fired boilers.

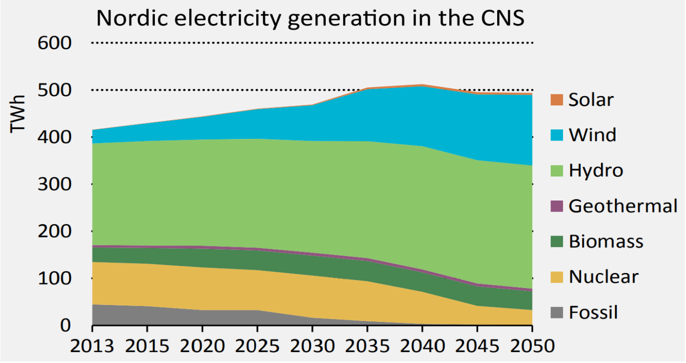

Fig. 1. Nordic electricity generation in the Carbon-Neutral Scenario, 2013–2050 [6].

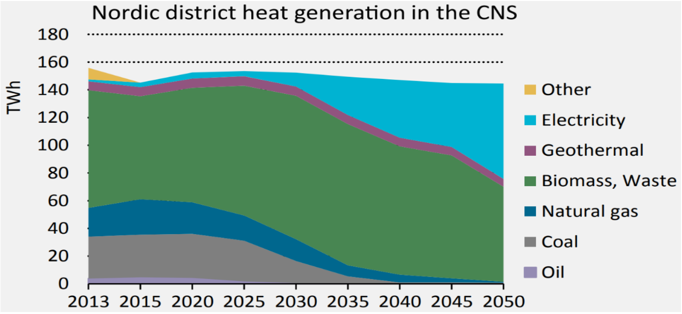

Fig. 2. Nordic district heat production in the Carbon-Neutral Scenario, 2013–2050 [6].

The scaled energy sector decarbonisation is characteristic of other countries, for instance, Germany, where electricity production from renewables (according to the installed capacity mainly solar and wind and less biomass and hydro) is still little behind the amount of electricity produced by fossil power plants (in line with the installed capacity mainly natural gas and coal and less nuclear), but overall trend is clear, i.e., the share of renewable generation is increasing and the share of fossil power plants is decreasing [7]. The questions to be addressed are "What challenges exist? and What broader lessons emerge from so rapid and scaled energy sector decarbonisation?”

The answers to these questions are reflected in Chapter 2. The main challenge is that the renewables threaten the existence of conventional generation, which has unfavourable consequences. The main lesson is that there must be the synergy between conventional generation and renewables.

In turn, Chapter 3 presents another synergy example – energy infrastructure cooperation (smart energy system) – which can help reach not only the decarbonisation dimension, but also other national energy and climate plan dimensions in a more proper way. For example, the electricity and gas systems interact continuously through a wide range of technologies, ranging from gas-to-power technologies (e.g., combined cycle gas turbine technologies) to power-to-gas technologies (e.g., electrolysis and methanation), via hybrid technologies (e.g., hybrid heat pumps). Closer cooperation between electricity and gas systems can help achieve climate goals in a more cost-efficient way by exploiting the synergies between the two systems [8].

During the period of 2025–2030 the electricity market of EU 28 might come to a state where average annual power demand could not be supplied by available conventional power plants (hydropower, natural gas, coal and nuclear). It is required to find solutions of major storage capacity of electricity generated by high-power, intermittent generation sources (wind and photovoltaics (PV)). Various mechanical, thermal, chemical and electro-chemical technologies are being studied worldwide.

Hydrogen has been deemed as one of the most promising energy carriers in more distant future. Extensive research efforts are devoted to resolve the issues of hydrogen storage. Accumulation and implementation of hydrogen reserves in existing power plants could ensure balancing of electricity consumption and production, adaptation to seasonal fluctuations and provision of energy reserves.

The ability to store hydrogen in a gaseous, liquid or solid state (as metal hydride) makes it suitable for projects of various scales. Hydrogen at various admixture levels can be directly injected into the existing natural gas grid. Electricity to the grid can be returned via gas turbines or fuel cell technology. Existing natural gas CCGT technologies can be readily adapted to operate on the admixture of natural gas and hydrogen.

However, estimated hydrogen electrolysis costs significantly exceed the price of natural gas, as well as a number of complex and unresolved technological and economic issues are raised:

- Injection of hydrogen into natural gas grid at a stable level;
- Hydrogen leak prevention;
- Storage and transportation solutions;
- Liquefaction of hydrogen gas;
- Safety and reliability issues.

More extensive use of hydrogen energy capabilities is projected after 2030.

Therefore, this article discusses approbated power generation technology solutions and opportunities.

2. RENEWABLES AND CONVENTIONAL GENERATION

The largest source of CO_2 emissions from the European OECD (Organisation for Economic Co-operation and Development) nations is energy, which accounts for 31 % of emissions [9]. Climate mitigation goals (greenhouse gas reduction) must be taken skilfully for the development of energy sector, i.e., the synergy should be between conventional generation and renewables. However, the opposite situation is observed: different support schemes for renewable energy sources (such as feed-in tariffs), large-scale integration of renewable energy sources and intermittent generation (solar photovoltaic, wind energy) in the energy production process and implementation of market mechanisms have changed [10], [11]:

- the running conditions of base load fossil fuel power plants (commercial conventional generation), i.e., the shifting from based load operation to cycling (new operation modes). It is the operation under variable condition, such as variable load of intermittent generation or fluctuation of electricity price. Baseload power plants are partly or entirely not adapted to the cycling operation, which leads to a decrease in their efficiency, more frequent trips and outages.
- the role of fossil fuel base load power plants, i.e., the secure integration of intermittent generation in energy production process and provision of regulation services to the transmission system operator instead of electrical and heat energy supply in line with its demand. This promotes the mass closing or mothballing of fossil fuel base load generation due to surplus of generation capacity, thus threatening the security of energy supply.
- the priority and significance of conventional generation. It is reflected in [10], [12], where the possible conflict was evaluated between the objectives of increasing the share of high-efficient cogeneration and renewable energy (biomass) using the example of Riga district heating system. The main consequences of conflict (natural gas cogeneration displacement with biomass), taking into account the situation in Latvia and neighbourly regions, were marked: decrease in primary energy savings; greenhouse gas emission increase; deterioration of electricity supply security; increase in the electricity price.
- the capability of conventional generation to participate in the development of wind generation. The reconstruction of fossil fuel power plants into biomass power plants and their mothballing provide unfavourable conditions for intermittent generation because a biomass generation unit has a lower flexibility level than commercial conventional generation (a natural gas power plant), which can excellently maintain electricity demand-supply balance. Moreover, biomass is an inefficient resource for electricity production. It is appropriate for heat energy production in terms of centralized and decentralized district heating system, where other more efficient power generation units are not used.

The excessive commitment to the climate mitigation issues have destabilised the energy sector triangle. It was emphasised by S. Ludge in [13]: "*Out of three* *pillars describing the energy sector triangle only one is developing positively. This is the environmental part, with the greenhouse gas reduction … and the increase of renewable energy production …. The other two pillars, being the cost competitiveness and the security of supply, are developing in the wrong direction".*

This wrong direction results in mothballing of the existing based load power plants and suspension of new projects. For instance, Germany has decided to shut down all nuclear power plants. Some of the European Union (EU) countries decided to abandon coal generation in 5–10 years. Moreover, some EU countries are not planning to develop fossil fuel generation in the near future. Thus, "manageable" generating capacity is continuing to decline in the European power system. It is an alarm not only for European transmission system operators, but also for decision-makers and politicians [7].

This trend is significantly critical for small quasi-isolated power systems. For example, the Baltic States are being currently integrated into the rest of EU electricity market mainly by direct current (DC) links. The integration of the Baltic States in Nord Pool has already brought substantial economic benefits for society through the decrease in the electricity price and price convergence among countries. However, penetration of renewable energy sources (RES) in production processes, in addition to electricity price fluctuations in some periods, has made the shift from base load to cyclical operation of fossil fuel power plants. The negative results appear in the decrease in power plant efficiency. It is vitally necessary to prevent these consequences, to adapt to a new situation and to achieve the dimensions of the national energy and climate plans in a more proper way. Penetration of renewables should be done deliberately and the flexibility of power plants should be enhanced [14].

Natural gas power plants are more advantageous than other conventional power plants (for example, brown coal or hard coal generation units) because they are more flexible, and natural gas is comparatively clean fossil fuel [15].

The flexibility of fossil fuel conventional generation is important not only today, but also within the next decades for the following reasons [10], [11]:

- to adapt existing generation to new running conditions and provide its efficient, flexible and profitable operation;
- to ensure the secure integration of intermittent generation in the energy production process and to ensure a stable energy system;
- to achieve the goal of the European Commission concerning renewable energy sources and energy efficiency.

The integration of renewables should be done competently preventing the displacement of conventional generation, i.e., there should be synergy between renewables and conventional generation in order to achieve climate mitigation goals without negative consequences.

There are different ways to achieve synergy between renewables and conventional generation, for example, the use of heat storage system to increase the flexibility of thermal power plants (TPP) and to adapt their operation to the variable operation conditions ensured by wide integration of renewables in the energy production process or by fluctuation of electricity price in the electricity market.

The flexible thermal power plants provide a more secure integration of intermittent generation in the energy production process and an opportunity to participate in frequency control. For instance, *Sandreuth* thermal power plant (Germany, Nuremberg) is loaded more, when the power of intermittent generation is not enough. The produced electricity is delivered to the electrical power network and heat energy – to the heating network. The surplus of heat energy is accumulated in the storage tank for its later delivery to the heating network. When there is enough power of intermittent generation, the load of *Sandreuth* thermal power plant is reduced to the minimal value or power plant is shut down. The intermittent generation mainly provides the demand of electricity and storage tank – heat energy. Thermal power plant ensures the small part of heat energy and electricity demand [11].

If the variable operation conditions are ensured by changing of electricity price in the market as it is in case of Latvia (lack of intermittent generation), then the installation of heat storage system ensures [11] (Figs. 3 and 4):

- the replacement of operation in mixed mode with running conditions in cogeneration mode, which ensures a more effective operation of the cogeneration unit, i.e., the decrease in natural gas consumption and CO_2 emission production;
- the increase of TPP competitiveness due to a decrease in fossil fuel power plant production costs;
- the extension of operation period, where thermal power plant electricity production costs are lower than the electricity price;
- the gain of additional profit from realisation of additionally produced electricity in the market.

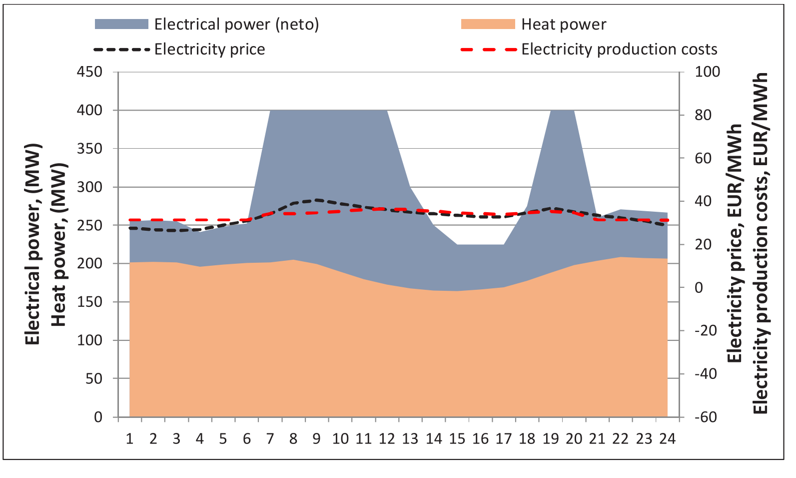

Fig. 3. Power of generation unit before the installation of heat storage system (one characteristic day) [11].

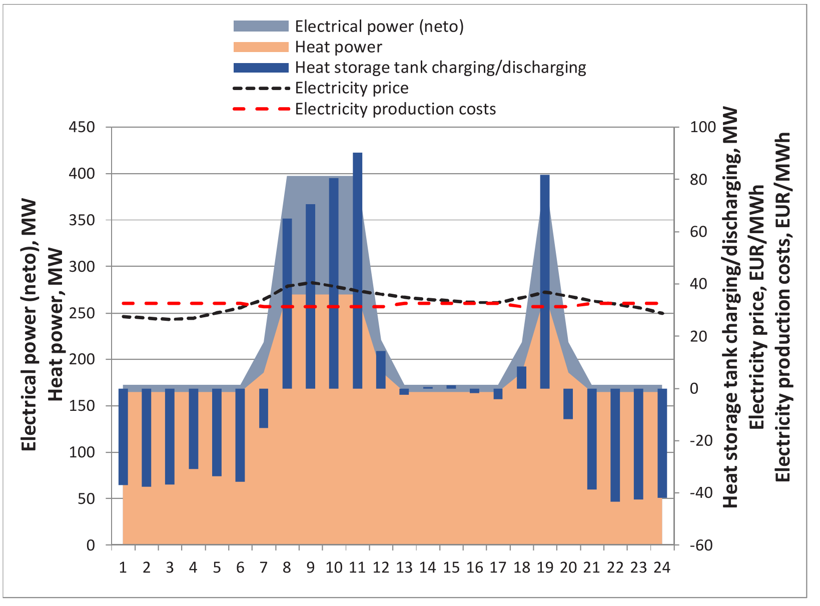

Fig. 4. Power of generation unit after the installation of heat storage system (one characteristic day) [11].

Formula (1) can be used to evaluate the amount of benefit (Π_k) gained from the adjustment of TPP to the situation in electricity market by heat storage system [11].

$$\Pi_k = \sum_i(m_i \times (\sum_j((C_j - MC_j) \times P_j) - C_{start-up})_i)_2 - \sum_i(m_i \times (\sum_j((C_j - MC_j) \times P_j) - C_{start-up})_i)_1, \quad (1)$$

where i – a characteristic day; j – hour in a characteristic day; m_i – the number of characteristic days (i) during a year, number; C_j – the electricity price per hour, EUR/MWh; MC_j – the electricity production costs per j hour, EUR/MWh; P_j – the supplied electricity per j hour, MWh; $C_{start-up}$ – start-up costs, EUR/start-up.

Another way to achieve synergy is the use of mathematical modelling instruments. Up-to-date forecasting and planning tools for the management of energy supply system are needed in order to ensure adequate and uninterrupted energy supply that complies with the requirements in respect to a secure supply system and environment. Energy system models are important instruments that allow analysing, forecasting, planning and optimally adjusting complex interactions between power engineering and environment, changes in technologies and energy consumption [10].

For example, in [10] the model has been created for the development of the energy system in Latvia, taking into account the specifics of energy supply in Latvia and the need to enable swift calculations (Fig. 5). The model comprises the possibility to analyse the evaluation of the integration of renewables on the operation of energy supply objects, the effect of resource prices, consumption dynamics, production capacities in energy resource generation, etc. The developed model comprises optimisation, system dynamics, econometric and algorithmic modelling elements.

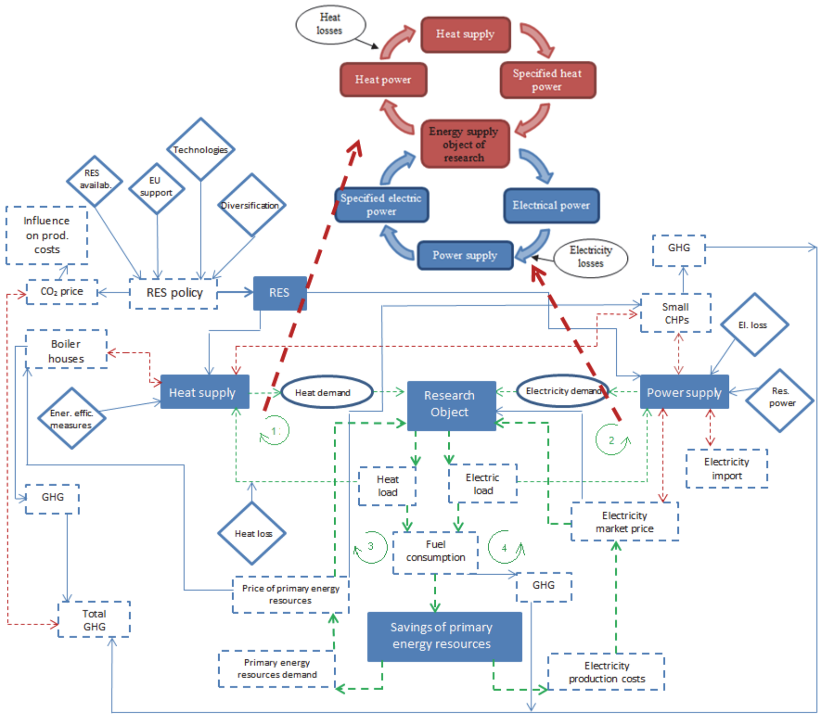

Fig. 5. Flowchart of the Latvian energy sectoral model [10].

The derived conclusions of modelling allow for a quicker evaluation of the quantitative indicators of the impact factors (e.g., wide renewable integration in energy production process) used for economic justification and management processes [10].

The practical modelling of the energy sector was accomplished considering the approbated technologies. In future, the modelling of optimal generation and accumulation might be supplemented with emerging technologies. Some of them, e.g., power-to-gas, are used in some research and pilot facilities. The analysis of forthcoming technologies might require significant tuning of the model in order to add more links among energy sectoral units. For instance, the electrolysis of hydrogen and methane production (CH_4) would allow for the continued use of existing natural gas infrastructure and applications, making extensive and revolutionary modernisation of power plants and appliances unnecessary.

3. SYNERGY OF GRID INFRASTRUCTURES

In simple terms, a smart energy system means combining the electricity, thermal and transport sectors so that flexibility across these different areas can compensate for the lack of flexibility from renewable resources, such as wind and solar power. The smart energy system is built around three grid infrastructures [16]:

- Electricity grids to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources, such as wind and solar power.

- Thermal grids (district heating and cooling) to connect the electricity and heating sectors. This allows for the utilisation of thermal storage in order to create additional flexibility and the recycling of heat losses in the energy system.
- Gas grids to connect the electricity, heating, and transport sectors. This allows for the utilisation of gas storage in order to create additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised.

The infrastructures of different energy resources are both competitive and complementary. The development of a new project or reconstruction can optimise the relevant distribution networks. The heating of building can be provided by: 1) electricity (heat pumps or heaters); 2) natural gas (installing the natural gas heat boiler); 3) thermal energy from a district heating system.

For instance, it is possible to refuse from gas, if a district heating system is available and used. If the cheap natural gas is available, it is possible to install microgeneration and refuse from electricity. Different combination of technologies (synergy) is possible, for instance, electricity and gas or electricity and thermal energy. The synergy of technologies provides significant financial benefits. Solving this optimisation task, the human desires and preferences should be taken into account. This increases the number of possible combinations. The price of primary energy resources, the costs of equipment and manpower (including disassembling), the lifetime of equipment, the efficiency of energy conversion process and maintenance costs should be taken into account proving the calculation of year-round expenditures. Different variants of change in energy resource price can be applied. If calculation is provided for one variant, the return of investments can be calculated using the NPV (net present value) method. It can be complicated to use *MS Excel* for the calculation of many variants and combinations. Therefore, the calculation should be provided by iteration. As a result, the minimum of expenditures is found (minimum total costs).

In simple terms, it can be expressed by the following formula (2):

$$Z_i = \sum_{t=1}^{T} (C_{j,t} + F_{j,t} + M_{j,t} - S_{j,t}), \quad (2)$$

where j – configuration; t – year; Z – objective function; C – capital investment; F – fuel cost; M – maintenance cost; S – salvage value.

Providing the calculation and comparison of objective function for each configuration, the lowest minimum total costs are found.

Similar computation is performed at the utility level for least cost investment planning and optimal generation expansion planning of whole countries [17]. Specific software models can also perform the assessment of specific energy and environment policies and measures, including price signals, such as taxation, subsidies, emission trading system, technology promoting policies, renewable energy source supporting policies, efficiency promoting policies, environmental policies and technology standards. Such models are used to analyse how to meet policy targets and price or cost of driving policies [18]. The model reflected in Fig. 5 contains two analysis loops reflecting the interaction between heat energy production and electricity generation. One of the interim results is the calculated saving of primary energy resources. The research object includes the relation of heat and electricity demand and comprises the amount of resources transported.

It is desirable to perform similar optimisation to the whole surrounding area, because the costs of infrastructure of heating mains and natural gas pipelines are large and the payback time depends on the intensity of its use. Usually the trenches of electric cables, the ditches of gas pipelines and heating mains do not coincide and electric cables, gas pipelines and heating mains are in want of their own trenches or ditches.

It is possible to freight more efficiently supply networks and common infrastructure by proving the optimised use of energy resources. The increase in electrical power network load ensures the lowest specific fixed costs, which partly refer to the unit of energy. The current situation is that there are areas, where there are still consequences of the Soviet time socialistic planning. Proving the optimisation of electrical power network infrastructures, it is possible to achieve higher consumption density. For example, the use of distribution network in Latvia is 7 408 GWh (2018) / 93 175 kilometre (2019) = 79.5 GWh / thous. km. However, the use of connection power of electricity power networks accounts for average 7 % in Latvia, but in the legal customers' sector – 16 % [19]. Latvia is comparable to Hamburg in terms of population. The power distribution network in Hamburg includes around 29 000 kilometres of power lines. The use of distribution network in Hamburg is 11.8 TWh / 29 000 km = 406.9 GWh / thous. km [20]. The network maintenance costs are lower in case of Hamburg. The connection power of electrical power network can increase significantly, if electrical technologies are used for heating.

4. CONCLUSIONS

The penetration of renewables is needed to ensure the energy mix and achieve the climate mitigation goals, but such penetration should be done deliberately in order to avoid undesirable consequences. However, nowadays the process of renewables mass penetration is launched and negative results are felt (the mass mothballing of conventional generation, the stability of energy supply is under the threat, the efficiency decrease of fossil fuel generation units, etc.). The reflected examples of synergies (cooperation between renewables and convention generation and cooperation among smart energy system grid infrastructures) present that it is vitally necessary to mitigate/prevent these negative results, to adapt to a new situation (variability of generation, new operation modes, urgency in ancillary services, lack of flexibility, etc.) and to achieve the dimensions of the national energy and climate plans in a more proper way.

REFERENCES

1. Eurelectric. (2019). *Short Paper on the 2050 Objective*. Available at https://www.eurelectric.org[08.07.2019]

2. 2030 Climate and Energy Framework (n.d.). Available at https://ec.europa.eu/clima/policies/strategies/2030_en [08.07.2019]
3. Kauliņš, D. (2019). *Presentation "Nacionālais enerģētikas un klimata plāns 2021. – 2030. gadam" materials*.
4. Eurelectric. (2018). *Decarbonisation Pathways. Full study results. Part 1 – European Economy. Part 2 – European Power Sector*. Available at https://cdn.eurelectric.org/media/3558/decarbonisation-pathways-all-slideslinks-29112018-h-4484BB0C.pdf [08.07.2019]
5. Sovacool, B. K. (2017). Contestation, Contingency, and Justice in the Nordic Low-Carbon Energy Transition. *Energy policy. 102,* 569–582.
6. IEA. (2016). *Nordic Energy Technology Perspectives 2016. Cities, Flexibility and Pathways to Carbon-Neutrality.* France: OECD/IEA. Available at https://www.nordicenergy.org/wp-content/uploads/2015/12/Nordic-Energy-Technology-Perspectives-2016.pdf [02.07.2019]
7. Balodis, M., Krickis, O., Gavrilovs, G., Sarma, U., Salcevičs, J., Lūsis, G., & Linkevičs, O. (2018). VFB kongress un IERE seminārs Minhenē. *Enerģija un Pasaule*, 5(112), 20–25.
8. Artelys. (2018). *Investigation on the interlinkage between gas and electricity scenarios and infrastructure projects assessment*, pp. 1–43.
9. *What are Europe's Biggest Sources of Carbon Emissions?* (n.d.) Available at https://www.weforum.org/agenda/2015/11/what-are-europes-biggest-sources-of-carbon-emissions/ [02.07.2019]
10. Balodis, M. (2016). *Optimisation model for securing energy supply towards sustainable economic development of Latvia.* Riga: RTU.
11. Ivanova, P. (2018). *The improvement of flexibility and efficiency of thermal power plants under variable operation conditions.* Riga: RTU.
12. Kunickis, M., Balodis, M., Sarma, U., Cers, A., & Linkevics, O. (2015). Efficient Use of Cogeneration and Fuel Diversification. *Latvian Journal of Physics and Technical Sciences, 52*(6), 38–47.
13. Ludge, S. (2017). The Value of Flexibility for Fossil-Fired Power Plants under the Conditions of the Strommarkt 2.0. *VGB Powertech*. 3, 21–24.
14. WEC 6th "Baltic Sea Round Table" (2019). Riga.
15. International Energy Agency. (2014). *Energy Technology Perspectives 2014. Harnessing Electricity's Potential.* France: OECD/IEA
16. Lund, H., Ostergaard, P., A., Connolly, D., & Mathiesen, B., V. (2017). Smart Energy and Smart Energy Systems. *Energy,* 10.
17. International Atomic Energy Agency. (1995). *Wien Automatic System Planning (WASP) Package.* Vienna: IAEA.
18. E3MLab/ICCS. (n.d.). *Primes Model 2013-2014.* Athens: E3MLab.
19. AS "Sadales tīkls" izpilddirektora Sanda Jansona intervija ar aģentūru "LETA", 13.06.2019. Available at https://www.sadalestikls.lv/sandis-jansons-jau-sobrid-jasak-vertet-mazo-elektribas-razotaju-ietekmi-uz-elektrotiklu-un-izmaksam/ [11.07.2019]
20. Wie der Strom zu den Hamburgern kommt (n.d.). Available at https://www.stromnetz-hamburg.de/ueber-uns/auftrag/das-stromnetz/ [11.07.2019]

NACIONĀLAIS ENERĢĒTIKAS UN KLIMATA PLĀNI: SINERĢIJAS SVARĪGUMS

Ā. Žīgurs, M.Balodis, P. Ivanova, K. Ločmelis, U. Sarma

K o p s a v i l k u m s

Enerģija, enerģētika mūsdienu pasaulē, t.sk. Eiropas Savienības valstīs, Baltijā, Latvijā, u.c. ietver plašu jēdzienu, sfēru un saturu, vairākus mūsdienu sadzīves un tautsaimniecības eksistences, komforta un drošuma nodrošinājumu. Arī tā aptver tādus segmentus kā siltums/siltumenerģija, transports/degviela, elektrība/elektroenerģija, energoresursi un to veidi.

Pareiza un plaša sinerģija starp dažādām enerģētikas jomām un enerģētiku un citām sfērām nodrošina iespējas risināt globālas problēmas, piemēram, klimata pārmaiņu mazināšana un ilgtspējīgas enerģijas izmantošanas nodrošināšana, samazinot siltumnīcefekta gāzu emisiju ražošanu, palielinot atjaunīgo energoresursu izmantošanā, sasniedzot lielāku enerģijas efektivitāti un nodrošinot saudzīgu energoresursu izmantošanu. Sinerģijas rezultātiem ir ekonomiskais svarīgums, tā nodrošina izmaksu efektivitāti un konkurētspēju optimālajā veidā.

Šajā rakstā sinerģijas nepieciešamība starp atjaunīgiem energoresursiem un konvencionālo ģenerāciju un sinerģija starp dažādiem enerģētikas sektoriem tiek apskatīta, lai sasniegtu Nacionālā enerģētikas un klimata plānu dimensijas.

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SYNERGY BETWEEN THE NATURAL GAS AND RES IN ENHANCEMENT OF SECURITY OF ENERGY SUPPLY IN THE BALTIC COUNTRIES (PROBLEM STATEMENT)

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Although the natural gas and renewable energy sources are two significant elements of the Baltic primary energy mix both today and in foreseeable future, the competitive edge of their usage often prevails over possibilities of mutually beneficial coexistence. Universally both forms of energy are often described as key elements of a transition to a cleaner and more secure energy future (low-carbon economy), but regionally much of the current discourse considers each in isolation or concentrates on the competitive impacts of one on the other. The paper outlines several potential avenues and further research trends of synergies between the natural gas, a proven fast-reacting fossil fuel, and RES as seen from viewpoints of the Baltic energy sector sustainability and security of energy supply.

Keywords: *decarbonisation, fast-reacting fossil fuels, natural gas, renewable energy, transitional technologies, synergy*

1. INTRODUCTION

In a global scale, consumption of natural gas and renewable energy (RES) has grown significantly in recent decades. Since 1990, natural gas consumption worldwide has doubled from 2000 billion cubic meters (m^3) in 1990 to almost 4000 (m^3) in 2018. In the United States alone natural gas demand increased by 10 % in 2018, the highest growth seen in the past 30 years, triggered by the power sector development (additional 15 gigawatts (GW) of new gas-fired power plants) and increasing consumption in the building sector. In 2018, RES covered 36 % of the power mix (including transport sector) in Europe, 26 % in China and around 18 % in the United States, India and Japan. The share of wind and solar in the global power mix rose last year by modest 0.8 %, but, as power generation accounted for more than 30 % of the total additional power production, the actual rise resulted in 16 % for solar power and 15 % for wind energy [1].

In the European Union (EU), past decades depict a constant, gradual decline in the natural gas and growth in RES. The share of RES in gross final energy consumption has almost doubled between 2016 and 2005. It reached 17 % in 2016 and 17.4 % in 2017. Overall increase in a share of RES in final energy consumption in the EU has slowed down a bit just recently, as increasing energy demand and lack of significant progress in a transport sector decarbonisation imperil the achievement of both 2020 targets on RES and energy efficiency [2]. At the same time, the statistics shows that consumption of the natural gas in the EU has been quite stable in recent few years and even shown signs of some positive dynamics. In 2017, gross consumption of natural gas in the EU increased by 3.7 % compared with 2016, to reach 18 587 thousand terajoules (TJ), but its use in the European energy production continued to demonstrate a downward pattern [3].

For large-scale natural gas infrastructure in the EU, in order to stay relevant, fulfillment of additional functions beyond its traditional role of transporting fossil fuel from the point A to point B is expected. Sustainability of the future natural gas networks will increasingly depend on their versatility, flexibility, and pricing of such commodities like carbon dioxide (CO_2) emissions and land use. Europe's natural gas infrastructure is a valuable asset, which should not be only preserved for sake of preservation, but utilised rationally to increase energy sector overall sustainability and enhance security of energy supply. The possibility to establish dynamic, integrated synergy between natural gas – regardless of its transportation means and final consumption sector – and RES till 2030 and beyond will define its role in decarbonized EU's energy future for decades to come [4], [5].

Optimistic prospects of growth in the natural gas consumption will most definitely await Europe's transport sector, where the role of LNG (liquefied natural gas) and CNG (compressed natural gas) is bound to increase in road and maritime (inland waterway) transport in the nearest future. There are rather rare examples of common European energy legislation, which directly connects decarbonisation of economy (transport or energy production sectors) with acknowledgment of the natural gas sustainability potential. Notable example of this rarity perhaps is Alternative Fuels Infrastructure Directive (2014/94/EU) supporting use of CNG and LNG as transport fuel and LNG as maritime and inland waterway fleet fuel [6].

In energy production and consumption sectors, no corresponding natural gas supporting pieces of legislation are in force, so there the natural gas sector should explore potential synergy avenues opened by new cornerstones of the EU energy policy framework – such as provisions of Energy Union (EEU) Governance [7], [8]. The National Energy and Climate Plans (NECPs) as the main tool of the EEU Governance for achieving the EU's 2030 climate and energy targets, clearly focus on at least: 1) 40 % cuts in greenhouse gas (GHG) emissions; 2) 32 % share for RES; 3) 32.5 % improvement in energy efficiency [9], [10]. These targets functionally supplement and specify five dimensions of the EEU for a period between 2021 and 2030, which are: 1) energy security; 2) the internal energy market; 3) energy efficiency; 4) decarbonisation of the economy; 5) research, innovation and competitiveness [11].

Decarbonisation of the economy is the only one of five dimensions, which allows for a kind of duality in terms of interpretation. On the one hand, its aim is a significant reduction of GHG emission, an increase in the share of RES in all energy and transport related sectors of national economies and an increase in the implementation of economically sound industrial scale CO_2 capture and storage solutions. On the other hand, this dimension relates to the so-called transitional technologies as well – mainly fossil generation solutions with a minimal environmental impact (maximal CO_2 neutrality) [5], [12].

Among these transitional technologies, which can provide: 1) stable base load generation during building and enhancement of large-scale market competitive RES; 2) reliable peak load generation during fluctuation in energy production from RES, only two stand out as most likely midterm coupling candidates (especially important for wind energy installations). They are nuclear generation units (reactors) and natural gas power plants [13]. Table 1 shows that in terms of direct CO_2 emissions per kilogram/kilowatt-hour (kg/kWh) and kilogram/gigajoule (kg/GJ), natural gas and nuclear reactors currently are less CO_2 intensive fossil fuels (generation sources) available.

Table 1

Direct CO_2 Emissions of Various Fuels

Fuel	Emissions: kg/kWh	Emissions: kg/GJ
Wood *	0.39	109.6
Peat	0.38	106.0
Lignite	0.36	101.2
Hard coal	0.34	94.6
Fuel oil	0.28	77.4
Diesel	0.27	74,1
Crude oil	0.26	73.3
Kerosene	0.26	71.5
Gasoline	0.25	69.3
Natural gas	0.20	56.1
Nuclear power reactors	0	0

* not sustainable used without reforestation
Source: *Fachbuch Regenerative Energiesysteme und UBA*

If nuclear energy provides CO_2 free base load generation, which can be successfully coupled with various RES and can also provide hydrogen production [14], the natural gas can ensure both base load generation (in cogeneration and condensation modes) and reliable peak load coverage thanks to its flexibility and fast fast-reaction properties [5]. Fast-reacting fossil fuel installations – such as highly efficient, combined-cycle, natural gas-fired power plants – in midterm EU and Baltic perspective could be regarded as one of the most viable options to: 1) ensure large-scale RES development, 2) guarantee energy security of supply, 3) avoid energy system crashes or interruptions (brownouts and blackouts); 4) support development and enhancement of existing large-scale natural gas transportation, storage and distribution networks. To date, large-scale storage of electricity cannot be easily and economically performed, so the amount of power generated from RES at the given time must exactly match the amount of actual demand [15]. Variability in generation has been identified as a significant barrier to the integration of large-scale wind and solar resources into energy systems [17], [13]. Currently, given their relatively low penetration in the Baltic States, the integration of RES has not required changes in system operations. Peak load generation technologies such as gas turbines have been used to compensate for variability, alongside other load-following generation technologies, such as large hydro power plants (HPPs). The same large RES balancing strategy is used in many European countries [5].

2. LARGE-SCALE WIND INTALLATIONS IN THE BALTIC COUNTRIES

In three Baltic countries, in foreseeable future large-scale RES, requiring reliable fossil fuel backup, could be onshore and offshore wind farms and, possibly, some solar PV installations. To date, in the three countries total installed wind capacity nearly reaches 900 megawatts (MW), [18], [19], [20] with Lithuania being a leader in the Baltic wind energy sector. There are currently 23 wind parks operating in Lithuania, with a combined capacity of 539MW. In 2018, they produced 1.1terawatt-hour (TWh) of electricity. By comparison, wind parks produced the largest amount of electricity in the Lithuania's wind energy history in 2017, reaching 1.3TWh [18].

As of the end of December 2018, there were 139 wind turbines installed in Estonia with a total installed capacity of 309.96MW. The last wind park commissioned to date is Tooma II with three turbines and total installed capacity of 7.05MW. It was inaugurated in 2016. In 2018, wind parks in Estonia produced 0.59TWh of electricity. Due to unfavourable wind conditions, production of energy decreased in 2018 by 12 % but remained at a similar level with 2016 [19].

In Latvia, installed capacity of wind is much more modest, and it riches around 67MW from which only 20.7MW are connected to the transmission network. Wind parks are mainly located close to the Baltic coast [20]. Future development of large-scale offshore and onshore wind energy installations still remains unclear as the Latvian National Energy and Climate Plan (LNECP) predicts rapid development of these installations only after 2023, with a possibility that in upcoming years (non-specified term) new offshore installations with total installed capacity up to 100MW could be built [21].

Historical study on RES development in 26 member states of the Organization for Economic Cooperation and Development (OECD) found that between 1990 and 2013 flexible fossil fuel backup capacity required for wind and solar was almost equal to the installed RES capacity: 1 % increase in the share of fast-reacting fossil technologies was associated with a 0.88 % increase in RES capacity in the long term [5]. It means that currently the Baltic countries require about 800MW of fossil fuel backup capacity for balancing their existing wind power installations, which cover almost all Riga combined heat and power plant 2 (Riga CHPP 2) electric load in cogeneration mode (two units combined: 832 MW) [25]. At the same time, rarely more than 10 % of wind installed capacities are producing energy simultaneously, so for extremely modest Baltic wind balancing only about 80MW would be required on a regular basis.

Synergy between the natural gas and RES in enhancement of security of energy supply in the Baltic region will become crucial when scarcity of flexible and market competitive fast-reacting base load generation (or base load generation as such) will step in after shutting down most of the Estonian oil shale generation units around 2020–2023 and the Baltic transmission systems' synchronisation area change in 2025.

3. FAST-REACTING NATURAL GAS GENERATION IN LATVIA

There are many options that might trigger achievement of the EU's 2030 climate and energy targets and enhance regional energy security. Diversification of the natural gas supply to the EU countries and internal market interconnection boost ensure reliability and sustainability of the natural gas both as power plants and in transport fuel [4]. Due to its physical properties, natural gas and its transitional technologies provide highly efficient energy production for all customer groups, from households to highly efficient cogeneration plants. State-of-the-art natural gas combustion technologies ensure competitive efficiency rates (>90 %) and are fully automated, depending on air temperature, day of the week and hours of the day, providing rational energy production and a high level of overall performance. Natural gas technologies therefore could be regarded as one of the most promising and cost effective transitional technologies for at least next few decades [23] in both EU and the Baltic countries, providing stable and reliable backup for emerging large-scale RES, in particular wind energy installations [24].

To date, RES generation backup has also been mostly provided through different fossil based technologies. Most base load fossil generation, for example, coal power plants running in condensation mode and nuclear power plants, cannot easily compensate for RES variability due to slow reacting times and high capital costs. Fast-reacting fossil technologies, which include most natural gas generation technologies (combined heat and power, integrated gasification combined cycle etc.) are characterised by quick ramp-up times, lower capital costs and modularity [25]. They are thus particularly suitable to meet peak demand and mitigate the variability of RES, especially large-scale wind installations [24].

Riga combined heat and power plants (Riga CHPP 1 and 2) are the most important base load generation units in Latvia and one of crucial base load units in the Baltic countries. With combined electric load of two Riga CHPP 2 units (832 MW (cogeneration mode) and 881 MW (condensation mode)) and one unit of Riga CHP 1 (144 MW), plants are mostly operated in the highly efficient cogeneration mode according to the thermal energy demand, which in turn depends on weather conditions and the duration of the heating season in Riga. Electricity generation at Riga CHPPs, especially Riga CHPP 2, is also directly influenced by the following market preconditions: electricity demand, natural gas and CO_2 price [22].

Riga CHPP 1 and 2 can be flexibly adjusted to the electricity market conditions and can cover Latvian electricity consumption almost completely when electricity import from foreign countries is limited. In 2018, both plants played a very important role in meeting the demand for electricity, when dry weather conditions significantly reduced the hydro energy output both in Latvia and throughout the Nord Pool region, and capacity shortages frequently hit regional interconnections. Last year Riga CHPPs generated about 2.6TWh of electricity and 2TWh of thermal energy, a 15 % decrease compared to 2017. The drop was due to the increase in competition in the thermal energy market: four new heat producers started operating in the thermal energy zones of Riga CHPPs at the end of 2017 – beginning of 2018.

Riga CHPPs' capability of fast start-ups is the most advertised flexibility feature in condensation and cogeneration modes. Cold state start-up time for both units of Riga CHPP 2 is > 55 hours (h), where "cold state" means that steam turbine temperature is below 210 °C. Time to launch cogeneration unit into operation from warm state (steam turbine temperature is in the range between 210 °C–410 °C) takes 8–55h, but from hot state (steam turbine temperature is above 410 °C) – < 8h. The rate of load increase and decrease corresponds to 16MW/minute. Number of allowed start-ups per year for units 1 and 2 are about 50 and 70 [25]. Therefore, Riga CHPP 2 generation units can provide a quick and prompt response to load fluctuations not only in Latvia, but also in other Baltic countries. In future, natural generation technologies will become even more flexible and responsive to market and physical demand dynamics. Even today there are natural gas CHPPs in operation in Europe, where new generation technologies provide maximum power output in less than 30 minutes (starting steam turbine temperature not specified), with a ramp rate of more than 50MW/minute [26].

Reduction of start-up time also reduces the adverse influence of modes on power plant operation, life time and energy production costs. The main economic gains are: 1) operating benefits lead to lower start-up costs; 2) ancillary services prompt to additional earning through ancillary service products; 3) market arbitrage induces higher profit trough usage of high price market [27]. Market compatible electricity wholesale price when one unit of Riga CHPP 2 can be operated in condensation mode is about 50 EUR/MWh (average day-ahead price in the Latvian Nordpool bidding area in January – July 2019 was 46.48 EUR/MWh).

In addition to flexibility provided by Riga CHPP 1 and 2, large-scale hydro is available in the Baltics thanks to three Daugava HPPs – the biggest in Latvia and the Baltic countries. As the Daugava is the river flowing across plains and the functionality of HPPs does not require energy consumption for reservoir filling, their ability to generate electricity depends on the water inflow of the Daugava River. In years with normal inflow levels (up to 200–250 cubic meters per second (m^3/s)), HPPs can operate at full capacity during the spring flooding season, which lasts for about one to two months annually. Outside the flooding season, the HPPs provide for the possibility to accumulate water and generate electricity when the demand and prices on the exchange are the highest. Daugava HPPs and Riga CHPPs work functionally sound together, as Riga CHPPs provide the major share of base load generation, but Daugava HPPs, whose share of base load generation fluctuates between 150 to about 350MW on seasonal basis, cover peak demand [22].

4. THE INCREASING ROLE OF CNG – BIOMETHANE SYNERGY IN TRANSPORT

Rare primary energy source can compete with the natural gas in diversity of use; however, dynamics of the natural gas market in Latvia over the past decades can be described as "free falling" with a rather modest outlook for significant positive changes in the nearest future. Natural gas consumption in Latvia decreased by about 40 % in last ten years, but since 1995, this decline had been even more impressive, reaching about 60 % (from almost 3 billion cubic meters (m^3) in 1995 to 1.2 billion m^3 in 2018) [28]. Almost the same pattern of decreasing natural gas consumption was observed in Estonia and Lithuania as well. Furthermore, Latvia's natural gas transportation and storage infrastructure, designed and built for much more intensive exploitation, now is used for only 40 % on the annual basis [20]. But at the same time, Latvia's natural gas security of supply rate (according to N-1 criterion and thanks to Inčukalns underground gas storage facility) is one of the highest in the EU [29], [30], [4].

While many European countries have quite reserved outlook towards sustainability of the natural gas, in other parts of the world, for example, in the US and Canada, moods are absolutely different. In these countries, natural gas, especially LNG or CNG used in municipal transport, is considered not only environmentally friendly fuel – a vital contributor to decarbonisation of economy, but also a "green" and sustainable form of primary energy [12]. The EU's Alternative Fuels Infrastructure Directive (2014/94/EU) is supporting the use of CNG and LNG as transport fuel and LNG as maritime and inland waterway fleet fuel. It establishes an obligation for the EU Member States to make LNG available in the maritime ports of the Trans-European Network of Transport (TEN-T) by 31 December 2025. It also addresses inland ports, which need to provide LNG bunkering infrastructure by 31 December 2030. Following the provisions of the Directive, Member States are obligated to prepare corresponding national policy frameworks to establish more than 250 LNG refuelling points throughout the EU until late 2025 [6].

The same document also establishes that an appropriate number of CNG refuelling points accessible to the public are put in place by 31 December 2020, in order to ensure that CNG vehicles can circulate in cities and other densely populated areas. Additionally, by the end of December 2025 Member States shall ensure that an appropriate number of CNG refuelling points are put in place, at least along the existing TEN-T Core Network, to guarantee circulation of CNG vehicles throughout the EU [6].

Biomethane and natural gas are recommended as fuels in urban traffic; the advantages of methane fuels related to noise reduction and emissions of harmful substances predispose them to be used in such fleets of vehicles as private cars, buses, municipal and delivery vehicles and taxis. Moreover, biomethane is currently the only biofuel with the same chemical composition as the fossil fuel it replaces. It can therefore be mixed with natural gas in any ratio, without negative consequences for the engine [31].

In the EU, demand for energy in transport is constantly growing, and, at the same time, the transport sector is almost entirely dependent on CO_2 intensive oil based fuels. Its pollution is responsible for more than 30 % of GHG emissions in Europe. Even in case of the most optimistic scenario regarding biomethane use in the EU future transport fuel mix, it could only cover 6.2 %–9.5 % of all transport energy needs. Only around 4 % of gas consumed in the EU comes from RES, and the share of "green" gas transported via a distribution grid makes up just 0.5 % compared to almost 30 % of RES in electricity generation, transportation and distribution. Less than 1 % of biomethane produced is currently used in transport [12]. In 2018, the EU leaders in number of CNG (CNG–biomethane) filling stations were Italy (1044), Germany (868), the Netherlands (176) and Sweden (174), but the Baltic States had just 18 CNG at all (Estonia – 13 (in 2019 – 15), Lithuania – 4 (in 2019 – 5), Latvia – 1 (in 2019 – 2)) [7], [17] [13]. Table 2 shows the number of CNG filling stations in the European countries in 2018 and the average price of fuel by country.

Along with second-generation biofuels and electric vehicles, biomethane is a promising option for enhancement of sustainable mobility [32]. The use of biomethane in energy production, consumption and transport opens one of the most important natural gas and RES synergy avenues, where the natural gas distribution grids can be used for transportation of biomethane. Such countries as Sweden, Germany, Italy and Estonia may serve as an example of effective implementation of CNG and CNG – biomethane partnership in transport. However, in these countries starting platforms are different: in Sweden natural gas grids are not used for biomethane transportation, but in Germany almost all biomethane is injected into natural gas grids. Non-grid transportation options are used only when natural gas grids (mostly, distribution networks) are not available in the vicinity of biogas production plants or are not developed at all, but injection into natural gas grids can be performed, when natural gas distribution networks are available and especially designed connection points are made in order to receive biomethane [32], [12].

While Latvia has just begun development of commercial CNG filling stations – the first commercial CNG filling station owned by JSC "Virši-A" was put into operation on May 16 this year in Jēkabpils [33] for serving seven CNG buses purchased by local municipal transportation authority –, its northern neighbour Estonia already has a lot of experience to share. The development of the Estonian CNG sector has come a long way, which stretches for almost a decade. First steps in its development were taken in 2008–2009. Interest of potential customers and availability of fiscal instruments for promotion of CNG played an important role in the process. In particular, during the start-up period for introduction of CNG in Estonia excise duties on natural gas as transport fuel were not collected at all. Currently excise duty amounts to 47.32 euro (EUR) per 1000 m^3, while excise duty free start-up is now applied to biomethane [34], [35], [16].

Geographically, CNG filling stations are spread evenly throughout the country, making CNG mobility easy, safe and reliable – without the risk of being left without a possibility to fuel a vehicle. Many stations have rather high performance capacities: for example, the CNG filling station in Parnu has a capacity of 17000 m^3/month (which corresponds to refueling demand of 18 city buses) [16]. The largest CNG filling station in Estonia to date is 48-unit refueling station in Tartu, put into operation in July, 2019. 64 new buses serving Tartu urban transportation network will be refueling at the new station. The section open for public can be used by the transport companies of Tartu region and private individuals [36]. In 2018, in Estonia 8.2 million m^3 of CNG was sold, 4.5 million m^3 of which was biomethane [34]. Figure 1 shows dynamics of the Estonian CNG sales during period between 2009 and 2018.

Table 2

The Number of CNG Filling Stations in the European Countries and the Average Price of Resources (€/kg)

Country	Number of stations	Average price of resources (€/kg)
Austria	169	0.99
Belarus*	44	0.32
Bosnia and Herzegovina *	2	–
Belgium	100	0.94-1.07
Bulgaria	114	0.75
Croatia	2	1.34
Czech Republic	171	0.97
Denmark	16	1.6
Estonia	13	0.86–0.9
Finland	37	1.34
France	77	1.24
Germany	868	0.95-1.08
Great Britain	6	0.78
Greece	13	0.86
Hungary	18	1.08
Iceland*	5	1.31
Italy	1044	0.96
Lichtenstein*	2	1.33
Lithuania	4	0.94**
Luxemburg	4	0.68
Macedonia*	5	0.62
Moldova*	19	0.40
Norway*	20	1.77
Netherlands	176	1.13
Poland	23	0.87**
Portugal	7	0.92**
Romania	3	0.94
Russian Federation*	235	0.27**
Serbia*	21	0.77
Slovakia	12	1.08
Slovenia	5	1.1
Spain	61	0.94
Sweden	174	1.87
Switzerland*	146	1.32
Turkey*	19	0.74**
Ukraine*	205	0.45**

* non-EU states ** €/m^3

Source: *cngeurope.com*

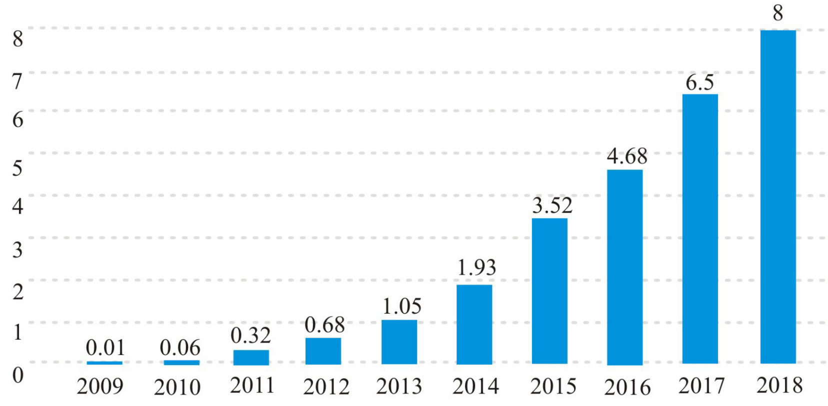

Fig. 1. CNG sales in Estonia (2009–2018, million m^3).
Source: *JSC Eesti Gaas*

Furthermore, Estonia allocated EUR 2 million in 2018 as support funds for the construction of biomethane plants (covering up to 35 % of construction costs or a maximum of EUR 350000 per project).

In order to catch up with its Baltic neighbours and to boost sales of natural gas as a transport fuel, the Latvian natural gas distribution system operator is estimating that at least 5 commercial CNG filling stations will be in operation in Latvia by 2020. Owner of Jēkabpils CNG filling station JSC "Virši-A" is willing to open two more station in 2019 in Riga [33].

In 2018, research was conducted in order to establish where conventional fuel filling stations are located in Latvia with proximity to the natural gas distribution network (potential locations for CNG filling units). The research results demonstrated that out of 250 stations owned by four operators natural gas grid connections (P<4bar min.; 300m or closer) were available in 130 places. Low-pressure natural gas grid connections (P<50mbar; 100m or closer) were available in 21 places, but a lack of natural gas distribution grid proximity was verified in 99 places. Table 3 reflects a breakdown of data, showing stations with grid connection proximity and lack of grid connection proximity [35].

Table 3

Existing Filling Stations in Latvia and their Proximity to Natural Gas Distribution Network

	Operator 1	Operator 2	Operator 3	Operator 4	Total
Number of filling stations	77	62	54	57	250
Natural gas grid connections available (P<4bar min.): 300m or closer	47	37	27	19	130
Low-pressure natural gas grid connections available (P<50mbar): 100m or closer	9	6	5	1	21
No natural gas distribution grid available nearby	21	19	22	37	99

Source: *JSC Gaso*

Development of expanded and prosperous CNG – biomethane market in the upcoming decade could be regarded as one of the cornerstones in both decarbonisation of the transport sector in the Baltic countries and revitalisation of national and regional natural gas markets, which struggle with consequences of a decrease in twenty year-long natural gas consumption and gradual changes in the market layout. It could also benefit to more intensive use of natural gas transportation, storage and distribution infrastructure, especially, if both CNG fueled vehicle and LNG fueled heavy duty vehicle segments take off in next five years as required by Directive 2014/94/EU. It reads that an appropriate number of refueling points for LNG accessible to the public must be put in place by 31 December 2025, at least along the existing TEN-T Core Network, in order to ensure that LNG heavy-duty vehicles can circulate throughout the EU [6] (according to certain estimates, LNG filing stations should be located max. 400 km apart along existing TEN-T Core Network and other main highways) [34].

5. CONCLUSIONS

In midterm perspective (2030–2040), the natural gas represents the shortest and least costly path towards decarbonisation of the energy sector in the Baltic countries, increasing its overall efficiency and level of security of supply, especially if reasonably coupled with various RES, which might be a viable option for the regional electricity generation and transportation sectors. The Baltic countries are a specific EU region, which in next ten years will face several challenges demanding meticulous planning of installed base load capacity development, such as change of energy system synchronization area in 2025, decreasing historical fleet of fossil base load generation in Estonia, transport sector decarbonisation efforts and rise in variable RES generation (large-scale wind installations) after 2020 [37].

In order to enhance the Baltic energy sector sustainability and security of energy supply via synergy between the natural gas and RES, the following conclusions can be drawn:

1. the parity between existing large-scale natural gas generation and large-scale RES should be clearly established, as large-scale natural gas generation provides reliable and flexible backup for large-scale RES, especially wind installations, which are most likely new large-scale RES to be actively developed in the Baltics [37];
2. parity of large-scale natural gas generation and RES benefits both sides: for RES it is a reliable backup, for the natural gas – predictable market positions and ability to enhance their flexibility parameters and the natural gas use even more;
3. this parity, as well as wider use of CNG/CNG–biomethane in transport will help to maintain an important asset – natural gas transport and storage infrastructure and intensify its use, especially storage capacities in Latvia, which also increase security of energy supply rates for the region;
4. contribution of sustainable natural gas technologies to the generation of electricity for use in electric mobility should be analyzed;

5. fiscal support mechanisms and municipal-state support programs for the construction of CNG and CNG-methane filling stations both on natural distribution grid and off-grid should be established;
6. biomethane segment of CNG fuel sector has to be developed in the three Baltic countries simultaneously, with future biomethane injections into natural gas grid. Sporadic development of off-grid filling stations is also welcome in areas without natural gas distribution network coverage;
7. taking into account that the start-up period is mostly unprofitable because there are not enough vehicles to fuel yet, close cooperation between state authorities and municipalities is a key to launch and expand CNG–biomethane market throughout the Baltic countries over the next decade.

Based on these conclusions, future research can be initiated in order to establish to what extent and by what means the most economically sound and technically unchallenging synergy can be reached between the natural gas and RES in the Baltic countries (in energy production – for balancing of large-scale RES, primarily, wind energy installations; in transport – for establishment and sustainable development of CNG–biomethane market).

ACKNOWLEDGEMENTS

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REFERENCES

1. Global Energy Statistical Yearbook. (2019). [Online]. [Accessed: 10 July 2019] https://yearbook.enerdata.net/
2. European Environment Agency. (2018). *Share of Renewable Energy in Gross Final Energy Consumption*. [Online]. [Accessed: 7 July 2019] https://www.eea.europa.eu/data-and-maps/indicators/renewable-gross-final-energy-consumption-4/assessment-3
3. Natural gas supply statistics. (2018). [Online]. [Accessed: 8 July 2019] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics&oldid=401136
4. Savickis, J., Zeltins, N., Kalvītis, A., & Ščerbickis, I. (2018). Natural Gas Development Prospects in the World, Europe, in the Baltic and Latvia. *Energy and World Special Edition* (dedicated to the 4th World Latvian Scientists' Congress), June 2018, Riga.
5. Verdolini, E., Vona, F., & Popp, D. (2018). Bridging the Gap: Do Fast Reacting Fossil Technologies Facilitate Renewable Energy Diffusion? *Energy Policy, 116,* 242–256.
6. Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure Text with EEA relevance. [Online]. [Accessed: 31 July 2019] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32014L0094
7. D'hont, L. (2018). *EU Energy Union: Old Wine in New Bottles?*. Master's Thesis, Ghent University. [Online]. [Accessed: 30 July 2019] https://lib.ugent.be/fulltxt/

RUG01/002/480/358/RUG01-002480358_2018_0001_AC.pdf

8. Wyns, T., Khatchadourian, A., & Oberthür, S. (2014). *EU Governance of Renewable Energy Post 2020 – Risks and Options*. A Report for Heinrich Boll-Stiftung European Union. Institute for European Studies, Vrije Universiteit Brussel. [Online]. [Accessed: 22 July 2019] https://www.ies.be/files/eu_renewable_energy_governance_post_2020.pdf
9. *2030 Energy Strategy*. [Online]. [Accessed: 31 July 2019] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy
10. *National Energy and Climate Plans (NECPs)*. (n.d.). [Online]. [Accessed: 31 July 2019] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans
11. Energy Union. (n.d.). [Online]. [Accessed: 30 July 2019] https://www.eceee.org/policy-areas/energy-union/
12. European Federation for Transport and Environment. (2018). *CNG and LNG for Vehicles and Ships – The Facts*. [Online]. [Accessed: 30 July 2019] https://www.transportenvironment.org/sites/te/files/publications/2018_10_TE_CNG_and_LNG_for_vehicles_and_ships_the_facts_EN.pdf
13. Sinn, H. (2016). Buffering Volatility: A Study on the Limits of Germany's Energy Revolution. *CESIFO Working Paper No.5950.*
14. Verfonder, K. (ed.) (2007). Nuclear Energy for Hydrogen Production. *Schriften des Forschungszentrum Jülich Reihe Energietechnik*, *58*.
15. GE Energy. (2008). Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements. [Online]. [Accessed: 20 July 2019] https://www.nrc.gov/docs/ML0914/ML091420464.pdf
16. Gaso. (2018). Summary on visit to Estonian CNG filling Stations (05.03.2018).
17. Mathiesen, P., & Kleissl, J. (2011). Evaluation of Numerical Weather Prediction for Intra-Day Solar Forecasting in the Continental United States. *Energy 85*, 967–77.
18. Lithuanian Wind Power Association. (n.d.). [Online]. [Accessed: 30 July 2019] https://lvea.lt/en/statistics/lithuanian-statistics/
19. Estonian Wind Power Association. (n.d.). [Online]. [Accessed: 30 July 2019] http://www.tuuleenergia.ee/en/windpower-101/statistics-of-estonia/
20. Litgrid, AST, Elering. (2015). *Review of RES Perspective in Baltic Countries till 2030*. [Online]. [Accessed: 30 July 2019] https://elering.ee/sites/default/files/attachments/Review_of_RES_perspective_in_Baltic_countries_till_2030.pdf
21. *Nacionālais enerģētikas un klimata plāns (Nacionālā enerģētikas un klimata plāna aktualizētā versija (PROJEKTS*)). (n.d.). [Online]. [Accessed: 30 July 2019] https://em.gov.lv/lv/nozares_politika/nacionalais_energetikas_un_klimata_plans/
22. Latvenergo (Generation). (n.d.). [Online]. [Accessed: 15 July 2019] https://www.latvenergo.lv/eng/about_us/generation/
23. IPCC. Climate Change. (2014). *Mitigation of climate change.* Cambridge: Cambridge University Press.
24. *Combustion Engine vs. Gas Turbine: Pulse Load Efficiency and Profitability.* (n.d.). [Online]. [Accessed: 31 July 2019] https://www.wartsila.com/energy/learn-more/technical-comparisons/combustion-engine-vs-gas-turbine-pulse-load-efficiency-and-profitability
25. Kuņickis, M., Balodis, M., Linkevičs, O., & Ivanova, P. (2015). Flexibility Options of Riga CHP-2 Plant Operation under Conditions of Open Electricity Market. In *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical*

Drives (POWERENG), (pp. 548–553). 11–13 May 2015, Latvia, Riga, Riga Technical University.

26. CDF. (n.d.). *CCGT: Improving the Environmental Performance of Fossil-fired Power Plants.* Online]. [Accessed: 18 July 2019] https://www.edf.fr/en/edf/combined-cycle-gas-turbine-power-plants
27. Ivanova, P., Sauhats, A., & Linkevics, O. (2016). Towards Optimization of Combined Cycle Power Plants' Start-Ups and Shut-Down. In *IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 7–10 June 2016, Florence, Italy.
28. Hokerts, J. (2019). Saspiestās un sašķidrinātās dabasgāzes ienākšana Latvijas tirgū – izaicinājumi un iespējas (presentation). In *Conf. Enerģētikas nozares nākotne – iespējas un izaicinājumi*. 7 March 2019, Riga.
29. Niedrite, I., Kreslins, A., Davis, A., & Zeltins, N. (2013). Security of Gas Supply Risk Assessment Alternatives. In *Proceedings of the 22th World Energy Congress, 820*(14). 17 October 2013, Daegu, Korea.
30. Jansons, L., Zeltins, N., & Savickis, J. (2016). The Latvian UGS Potential and Alternative Use of Underground Geological Structures. In e_*Proceeding of the 23rd World Energy Congress*. 9–13 October 2016, Istanbul. ISBN: 978-605-89548-9-2
31. Rogulska, M., Bukrejewski, P., & Krasuska, E. (2018). Biomethane as Transport Fuel. [Online]. [Accessed: 30 July 2019] https://www.researchgate.net/publication/326376873_Biomethane_as_Transport_Fuel
32. Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., & Brückmann, R. (2016). *Optimal Use of Biogas From Waste Streams. An Assessment of the Potential of Biogas from Digestion in the EU Beyond 2020*. CE Delf. [Online]. [Accessed: 30 July 2019] https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf
33. Virši-A. (n.d.). Atklāj pirmo CNG jeb saspiestās dabasgāzes staciju Latvijā. [Online]. [Accessed: 10 July 2019] https://www.virsi.lv/lv/atklaj-pirmo-cng-staciju-latvija
34. Eesti Gaas. (2019). CNG and LNG in Europe and the Baltic (presentation). In *Conf. Enerģētikas nozares nākotne – izaicinājumi un iespējas*. 7 March, 2019, Riga. [Online]. [Accessed: 5 June 2019] http://konferences.db.lv/conferences/energetika-2019/
35. Gaso. (2018). CNG transporta un uzpildes infrastruktūras attīstības perspektīvas (presentation).
36. *Estonia: Largest CNG Filling Station Opens.* (n.d.). [Online]. [Accessed: 31 July 2019] https://www.petrolplaza.com/news/22348
37. AST. (2018). *Pārvades sistēmas operatora ikgadējais novērtējuma ziņojums.* [Online]. [Accessed: 5 July 2019] http://www.ast.lv/sites/default/files/editor/20181001_PSO_Zinojums_2017.pdf
https://www.ies.be/files/eu_renewable_energy_governance_post_2020.pdf
38. Zemite, L., Kutjuns, A., Bode, I., Kunickis, M., & Zeltins, N. (2018). Consistancy Analysis and Data Consultation of Gas System of Gas – Electricty Network of Latvia. *Latvian Journal of Physics and Technical Sciences, 2018*(1), 22–34 (DOI: 10.2478/lpts-2018-0003)

DABASGĀZES UN AER SINERĢIJA BALTIJAS VALSTU ENERGOAPGĀDES DROŠĪBAS PAAUGSTINĀŠANAI (PROBLĒMU NOSTĀDNE)

J. Savickis, N. Zeltiņš, L. Jansons

K o p s a v i l k u m s

Lai gan dabasgāze un atjaunojamie energoresursi ir divi nozīmīgi Baltijas valstu energoapgādes elementi gan šobrīd, gan pārskatāmā nākotnē, to konkurences aktualizācija prevalē pār abpusēji izdevīgas līdzāspastāvēšanas uzstādījumu. Globālā mērogā dabasgāze un AER arvien biežāk tiek uztverti kā galvenie pārejas uz oglekļa mazietilpīgu ekonomiku elementi, taču Baltijas valstu kopīgās enerģētikas nākotnes diskusija vairāk vērsta uz to pretnostatīšu, nevis konstruktīvas, abpusēji izdevīgas un tehniski pamatotas līdzāspastāvēšanas iespēju meklējumiem. Rakstā aktualizēti vairāki perspektīvi pētījumu un praktiskās darbības virzieni, kas vērsti uz dabasgāzes, pārbaudīta ātri reaģējoša fosilā kurināmā, un AER sinerģiju Baltijas valstu energoapgādes drošības paaugstināšanai un ilgtspējas stiprināšanai.

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ECONOMICAL VALUATION OF WAVE POWER PLANT IN THE BALTIC SEA REGION AT PRE-FLEXIBILITY STAGE

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The article deals with free surface gravity waves as one of the alternative energy sources and their use. The potential of the waves and their transformation devices are considered as the main energy use impact factors. The goal of the research is to perform a cost-benefit assessment. The following tasks have been set: to make an assessment of wave potential, to identify the conversion model and turbine, to determine economic criteria taking into account wave and price variability. The article also provides the description of the theoretical valuation of the costs of the mentioned turbine power plant.

Keywords: *axial turbine, renewable energy, wave energy, wave length, wave power, wave power plant, wave propelled turbine.*

1. INTRODUCTION

The 21st century is a period of hasty growth in world population, production and consumption of fossil fuels (FF). World population increased approximately 10 times in the period of 1819–2019 [1]. Such an increase significantly influences global energy demand. Consequently, total world energy consumption in the last 200 years rose about 22 times [2].

According to the World Energy Council calculations [3], coal is the most abounding FF, whose reserve is enough for about 130 years. However, the global climate change poses a problem for the use of energy and especially for the use of FF [4]–[7]. The global use of coal, oil and gas leads to a rapid growth in carbon dioxide emissions. Global energy-related CO_2 emissions increased up to 1.7% in 2018 to achieve a historic value of 33.1 Gt CO_2. It was the peak ratio of increase since 2013, and 70 % higher than the average growth since 2010 [6]. Such CO_2 growth contributes to the greenhouse effect and global warming. Since the 1880s, world temperature has increased by about 0.8° Celsius (1.4° Fahrenheit) [8]. As a result, observations show a significant increase in the level of natural disasters and imbalance of different water states. Summing up, greenhouse gas emissions need to be controlled, and in the world of growing energy demand, renewable energy sources (RES) look like to be the best solution.

Nowadays the European Union (EU) plays the main role in the development of RES. For several years, the EU has been tackling climate change according to the main European policies such as the Renewable Directive 2009/28/EC, Renewable Energy Directive (2018/2001), Energy Efficiency Directive 2012/27/EU, Paris Agreement, etc. The EU is now committed to decreasing greenhouse gas emissions to 80 %–95% below 1990 levels by 2050 [4].

As a result, renewable energy has become the top priority in most developed and some developing countries. According to Renewable Energy Statistics [3], the quantity of renewable energy raised overall by 64.0 % between 2007 and 2019, equivalent to an average increase of 5.1 % per year. The most significant source in the EU-28 is wood and other solid biofuels. The next most important contributors to the renewable energy are wind and hydro power. Biogas, liquid biofuels and solar energy make up 7.4 %, 6.7 % and 6.4 %, respectively, of the total share of EU-28 renewable energy produced in 2017. There are currently low levels of tide, wave and ocean energy production. However, the wave energy is a promising energy source. It has the highest potential in terms of energy production, which makes it more interesting to investigate.

Wave energy has several important advantages compared to solar and wind energy. First, waves have a higher energy density [7]–[8]. Second, the wave energy is predictable one to two days ahead because satellites can measure waves in the ocean, which will subsequently affect devices around the coast. This predictability will afford a smaller margin than is often required to support more volatile RES. Third, wave energy does not require land area, driveways and devices to collect energy of a smaller size than devices for wind power.

Wave energy is one of RES, which is the untapped resource and currently is at an early stage of development [7]–[8]. It is estimated that global wave power potential is equal approximately to 1 TW, which is an enormous and impressive value. Furthermore, world's potential is 10000–15000 TWh per year [7]. This is nearly the same as the economic potential in the range of wind and hydropower in the world. However, other scientists who have studied the potential of surface water gravity waves in the world have estimated from 8,000 TWh/year till 80,000 TWh/year [9]. According to the Ocean Energy Statistics report of 2018 [10], Europe occupies a leading position in wave energy installation, which is equal to 11.3 MW.

There is a wide range of wave energy technologies. Each technology uses different solutions to absorb energy from waves, and can be applied depending on the water depth and the location [7], [11]–[13]. In recent years, various onshore and offshore projects have been developed, including the Islay plant (Scotland) and the Pico Island plant (Portugal) [11], [14]. Continuing the investigation of the wave energy, many countries have seen some development in the planning, installation, and operation of wave energy converters (WEC). However, the amount of WEC is still at the Research and Development (R&D) stage. There are a very limited number of WEC devices that are suitable for a commercial pilot demonstration stage [15]. However, since 2008, the European Commission has invested over 190 M€ in ocean energy research and innovation through different projects, such as *Horizon 2020* and

Interred programmes [16]. Currently, plans and projects are being developed in the near future to get EU support and private investment for wave energy development [18]. With the rapid development of the technologies of WEC, the wave source will be able to meet partly the demand of energy.

The creation of new wave power plants (WPP) requires considerable material, financial and labor resources. Therefore, a feasibility study should be carried out to determine the proportion of funds for the construction of new WPP and to estimate the payback period of WPP.

The paper focuses on the free surface gravity waves and their potential in the Baltic Sea. Moreover, we developed and described a new turbine type – an axial self-regulation blade hydrokinetic turbine that formed the basis of all calculations. Consequently, the main goal of the paper is to clarify the economic feasibility of the possible construction of marine WPP based on the developed hydrokinetic turbine.

2. WAVE POTENTIAL OF THE BALTIC SEA

According to [9], [17], [18], the wave potential of the World Sea with some exclusions is 29 500 TWh/year. The Baltic Sea is the large sea, which is bounded by the coastlines of 9 countries. In the Baltic Sea alone, the potential is estimated to be 24 TWh [7]. It should be noted that global processes, such as global climate change, affect the Baltic Sea region and correspondingly wave energy production in the region. The theoretical wave power reserve of the Baltic Sea is calculated to be 1 GW [19]. The EU Strategy for the Baltic Sea was approved in 2009 [20]. The aim of this strategy is to make the area of the Baltic Sea more environmental, energy-generative, attractive and safe.

The potential of the Baltic Sea is actively studied despite the fact that there are more successful aquatories in the world. For instance, scientists Soomere and Eelsalu [22] have described a study of both the theoretical amount of wave energy and its practically available part in a medium-depth aquatorium on the east coast of the Baltic Sea. The 38-year average wave power is 1.5 kW/m, but in some places it reaches 2.55 kW/m, in the Gulf of Finland and in the Gulf of Riga – 0.7 kW/m. The most important factor is that this water area has an uneven distribution of wave energy during the year. The visualization of the medium depth wave power of the Baltic coast is shown in Fig. 1.

The nodal points shown are 3 nautical miles apart. Results of specific wave power have been produced from 37-year period initial data. Unlevel specific wave power results shown depend on the distance of wave propagation and depth at the nodes. To get more accurate wave power data, the exploration should be led to deep water direction.

There are different methods for determining the potential of waves [18], [21], [22]. These methods have gaps [23]. To mitigate the weaknesses of the above methods in the wave power estimation, we propose a Wave Energy Direction Baseline Projection (WEDBP) method [23] whose initial calculations correspond to the classic irregular wave calculations. The method differs from others by selecting basic base directions +/- 22.5^{o} and by these sectors the specific power and specific energy of the node points are summed. Then there are polygons around the node points that cover the area of the aquatorium, if it is necessary to mathematically model additional node points and sum up the results [23]. With WEDBP method it is possible to cover a large area of the aquatorium with a small amount of nodal numbers and therefore input data.

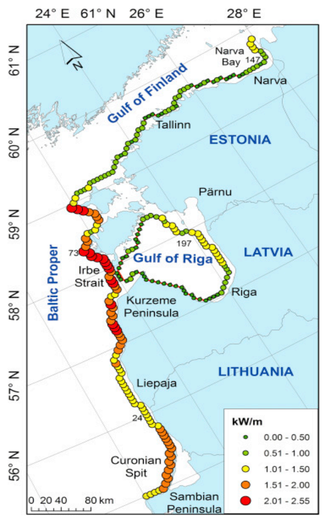

Fig. 1. Visualization of the medium depth wave power of the Baltic coast according to Tarmo Soomere and Maris Eelsalu [18].

Input data used for energy, power and wavelength calculations are significant wave height (H_{si} or *swh*), wave period (T_e) and mean wave direction (*mwd*) [10].

Energy calculations were performed by algorithm of the WEDBP method:

From the energy spectrum by integrating in the frequency range [0; let us calculate the average wavelength energy density of J_{vid} in the area of 1m^2 [24]:

$$J_{vid} = \rho g \int_0^\infty S(f)df = \rho \cdot g \cdot m_o = \frac{\rho \cdot g \cdot H_{m0}^2}{16} = \frac{\rho \cdot g \cdot H_S^2}{16}, \quad (1)$$

where p – Seawater density, kg/m^3; g – Free fall acceleration, m/s^2; f – wave frequency (Hz); $S(f)$ – wave energy spectrum function; m_0 – 0-th spectral moment; $H_{m0} = H_s$ – characteristic wave height, m.

1. In the Baltic Sea Area “A” perpendicular to 8 traditional wind and wave directions (PV_{xx}, where xx = (N; NE; E; SE; S; SW; W and NW) let us set the lines perpendicular to those directions.

Thus, summing the wave direction of energy (1) over time interval in each of the node points by sector, the wave energy of non-duplicate directions is counted:

$$\dot{E}n(Km, PV_{XX}) = \Delta t \cdot \frac{\rho g^2}{64\pi} \sum_{i=1}^{n} IF(mwd_i, PV_{XX,min}, PV_{XX,max})(T_{ei}(H_{si})^2), \quad (2)$$

where PV_{xxmin} – the minimum limit for basic PV_{xx} sector; PV_{xxmax} – the maximum limit for PV_{xx} sector; H_{si} – the significant wave height in the i-th time interval, m; $T_{e\,i}$ – the average energy period of wave energy density spectrum, s.

The annual wave energy potential of the control point P_m for a 1m wide wave $\dot{E}_g$ is calculated as follows:

$$\dot{E}_{g,m,xx,yy} = \sum_{n=1}^{12} (E_{n,,m,xx,yy}). \tag{3}$$

2. Integrating the direction of the reference line control points into the corresponding energy by integrating its specific energy function within the distance projection. Thus, the integration process is reduced to the use of trapezoidal method [25], which is as follows:

$$E_{xxyy}(K1, K5) = \sum_{m=1}^{m+1=5} E\,(\Delta L(m, m+1)_{xx} = \sum_{m=1}^{m+1=5} \frac{\dot{E}n(K_m)+\dot{E}_n(K_m+1)}{2} \cdot \Delta L(m, m+1)_{xx} \quad , \tag{4}$$

where m – the node point $P_{m,xx}$ serial number (1, 2, 3, 4, 5, 7); ΔL (m, m + 1) – the distances (m) between these point projections on the base line, taking into account the coordinates of the azimuth and control points of the baselines.

3. Knowing the potential of wave energy in the control area where control points P1 are located; P2; P3; P4; P5 and P7, which are marked by the projections of the checkpoints on the base lines of the direction (Fig. 2) and knowing that the control area forms a significant, but not the whole, part of the analyzed area and knowing that the distribution of wave energy in time and space is dispersed homogeneously, it is possible to estimate the amount of PV_{xx} energy for each proportionally increasing ratio of direction of the reference line P_{nyy} and the sum of the respective projection sections of the node points L (P1, P5)$_{yy}$.

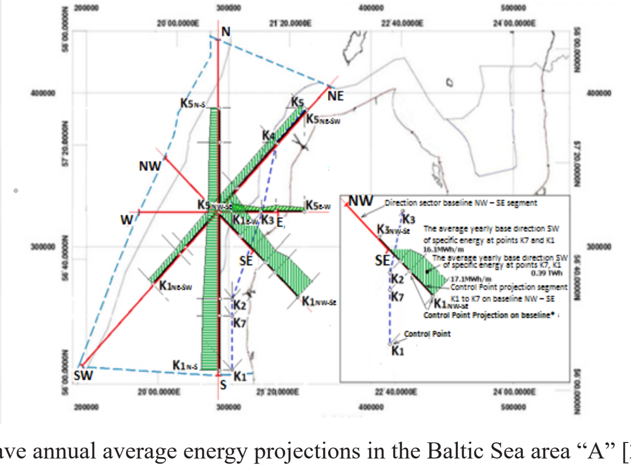

Fig. 2. Wave annual average energy projections in the Baltic Sea area "A" [24], [27].

4. As a result of calculation of any aquatorium potential, the total monthly/ annual wave potential is the sum of 8 potentials.

In the Baltic Sea, 7 node points of Latvia's Exclusive Economic Zone (EEZ) were selected, for which we received input data from the Danish Meteorology Institute (DMI) and a number of calculations were made for five years (Table 1).

Table 1

Schedule of the Baltic Sea Latvian EEZ Wave Potential Calculations

Names of calculations	Node points						
	P1	P2	P3	P4	P5	P6	P7
$E_{monthly}$ depending on H_{si}/T_e	2010–2014						
$E_{monthly}$ depending on H_{si}/T_e	2010–2014						
$E_{time\ distribution}$						2010	
$P_{specific}$ depending on H_{si}	2010–2014						
$P_{wave\ specific}$ time distribution	2010–2014						
Distribution of waves by λ intervals	2011						
$E_{specific}$ P5 distr. by *mwd* & month					2010–2014		
$E_{specific}$ P5 distr. by month					2010		
$E_{specific}$ P5, P6, P7 distr. by month					2010–2014		
$E_{specific}$ P6 distr. by *mwd* & month					2010–2014		
$E_{specific}$ P7 distr. by *mwd* & month					2010–2014		

Note: $E_{specific}$ monthly is distribution of wave energy potential by month, kWh; $E_{specific}$ time distribution is wave energy distribution by time kWh/m; $P_{specific}$ depending on H_{si} is wave power dependence of significant wave height, W/m; $P_{specific}$ time distribution is wave power distribution by time, W/m; λ is wavelength, m; $E_{specific}$ P5 distr. by *mwd* & month is specific wave energy distribution by mean wave direction and by month at node point No 5, kWh/m; $E_{specific}$ P5 distr. by month is specific wave energy distribution by month at node point No 5, kWh/m; $E_{specific}$ P5, P6, P7 distr. by month is specific wave energy distribution by month at node point No 5, kWh/m; No 6 and No 7; $E_{specific}$ P6 distr. by *mwd* & month is specific wave energy distribution by mean wave direction and by month at node point No 6, kWh/m; $E_{specific}$ P7 distr. by *mwd* & month is specific wave energy distribution by mean wave direction and by month at node point No 7, kWh/m.

3. EQUIPMENT CHOICE

In cooperation with Riga Technical University, at least 108 current developments were considered. In the beginning, more than 109 installed and under development devices were examined [27]. Then the classification of equipment was made according to suitability of installation for onshore, nearshore and offshore. Afterwards, the type of equipment was selected from the perspective of options to elevate receiver and to position to *mwd*. Finally, the axial turbine with vertical axis and self-regulating blades (SAB) was chosen.

4. CONCEPT OF SELECTION OF TURBINE DIAMETERS

Figure 3 shows a new type of turbine – an axial self-regulating blade hydro-kinetic (ASRBHK) turbine. It was tested under laboratory conditions.

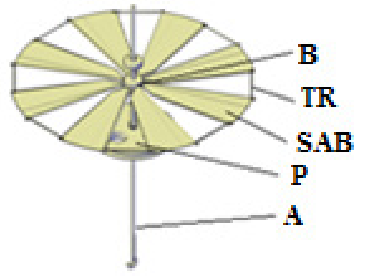

Fig. 3. ASRBHK turbine construction (B – bearing, TR – tensioning rubber, SAB – self-adjusting blade (SAB), P – pulley, A – axis) [28].

Various torqueses are formed on the ASRBHK turbine during its various phases and in the turbine wing positions. Turbine works more efficiently when the number of wave phases is as small as possible. Each wave has four phases. The smallest number of phases, which crosses the turbine wing, is two. For this reason, it is worth looking at the length of SAB depending on the wavelengths. Let us look at one of the areas of the Baltic Sea's Latvian EEZ (for example, the data of node point P1 in 2010) (Fig. 4).

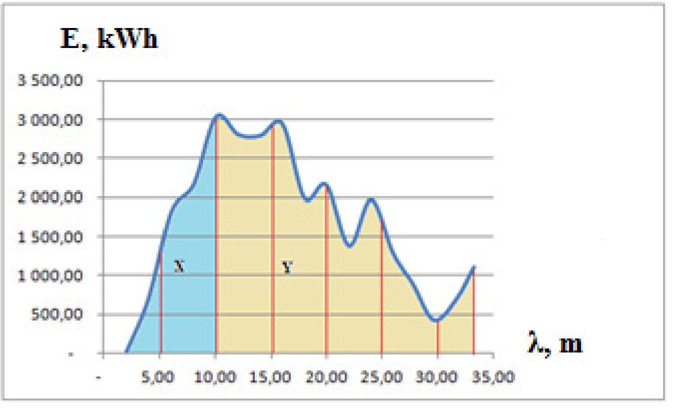

Fig. 4. Distribution wave energy at node point P1 2010 depending on λ/4 (m).

Figure 4 shows that enough wave energy will be in the area X where ¼ of the wavelength will be 10 m. This means that the maximal turbine diameter could be 20 m. Meanwhile the minimal diameter would determine some other parameters like drop of efficiency and/or too high costs. In the area Y shown in Fig. 4, the turbine of any diameter will work with partial wave power. It should be deepened in order to avoid overloading.

5. TURBINE POWER CALCULATION

To determine turbine power, we combine and stack two methods – an experimental one to determine turbine model power and a mathematical method to determine industrial-sized turbine power. In order to find out the parameters of the turbine model, turbine models were made for which the shape of the self-adjusting blade was sub-optimized. The laboratory wave stand had the ability to change the wave parameters (*H* and *T*). In order to determine the capacity of an industrial-sized turbine, we considered the specific power frequency of the potential P1 wave power plant in the Baltic Sea. This is essential for providing the turbine with optimum load. For the transition from the turbine model to the industrial size, let us use the Morozov's equation [24] before creating a special relationship more suitable for this mechanism.

In order to identify the duration of the waves of particular average power, we will create hourly statistics, for example, node point P1 2010 (Fig. 5).

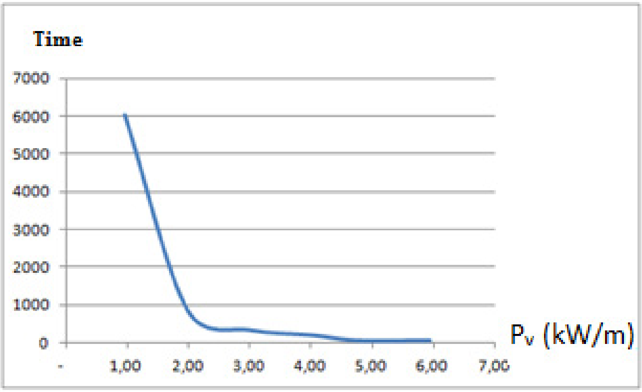

Fig. 5. Wave average hourly specific power P_v (kW/m) statistics at node point P1 (2010).

By optimizing the peculiar incoming energy of the mentioned node point, the result was the optimum specific power of 1 kW/m.

The coefficient η_T is used to determine the efficiency of transformation from wave energy to electricity and can be characterized by equitation (2):

$$\eta_T = \eta_V \times \eta_H \times \eta_P \times \eta_F \times \eta_L \times \eta_M \times \eta_E \,, \tag{5}$$

where η_V – the kinetic energy distribution coefficient in volume; η_H –the horizontal flow separation ratio (0.5); η_P – the flow utilization factor for estimating the flow through the turbine (Beitz/Glauerts 0.5926) [29]; η_F – the form factor (π/4); η_L – the turbine hydraulic efficiency; η_M – the mechanical efficiency (bearing, seal 0.95); η_E – the efficiency ratio of the electric generator (for calculations we will use 0.95).

Morozov's equation (6) describes the relationship of the known ASRBHK turbine T_1 model and geometric similar turbines T_n with diameter D_n (6):

$$\eta_{Ln} = (1 - (1 - \eta_{L1}) \times \sqrt[5]{\frac{D_1}{D_n}}, \tag{6}$$

where η_{Ln} – the efficiency coefficient of a geometrically similar turbine; η_{L1} – the efficiency ratio of known turbine; D_1 – the diameter of known turbine (0.9 m); D_n – the diameter of the geometrically similar turbine.

Assuming η_{T1} and η_{Tn} expressions based on equation (5), dividing both of these equations with each other and by deducing the same variables we will express them as equation (7):

$$\frac{\eta_{T1}}{\eta_{Tn}} = \frac{\eta_{L1}}{\eta_{Ln}}. \tag{7}$$

From (7) known turbines η_{L1}:

$$\eta_{L1} = \frac{\eta_{T1}}{\eta_V \cdot \eta_H \cdot \eta_P \cdot \eta_F \cdot \eta_M \cdot \eta_E}, \tag{8}$$

where all the values on the right of the equation are known. Thus, knowing η_{Ln}, η_{L1} and η_{T1} from expression (8), the coefficient of utilization of the geometrically similar turbine η_{Tn} is calculated. Calculations of η_T for ASRBHK turbine of different diameters from 1 m to 30 m with step in 1 m were made.

Turbine utilization rate was estimated based on turbine (D = 0.9 m, P_w = 0.764 W/m only) parameters. This means that incoming power of turbine (D = 9.0 m) is only 0.08 kW, turbine (D = 15.0 m) is only 0.21 kW and turbine (D = 20.0 m) is only 0.38 kW. For more powerful waves, the turbine utilization factor will improve. For our further calculations we will use assumption that average turbine utilization rates are appropriately D = 9.0 m – 0.25.

6. ECONOMIC ASPECTS

A. Forecasting Wave Energy Production

Price forecasting is the basis for solving a wide range of important problems for planning and managing the energy sector, and feasibility study of wave energy production is not an exception. A great number of methods from different modelling families are used for analysis and planning questions [30]. Comprehensive reviews of pricing approaches are provided in the articles [30]–[32].

To analyze the feasibility of presented WPP, a net present value (NPV) and a payback period (PP) for the planning period T_p (in our case 34 years) should be estimated. In NPV criteria value assessment, the greatest difficulty is related to calculation of the net cash flow R_t because of the change of the energy prices over time. In our case, the R_t (€) is calculated as follows:

$$R_t = P_{rat,t} \cdot \tau \cdot L_{WPP} \cdot k \cdot C_t, \quad (9)$$

where $P_{rat,t}$ – rated specific wave power per hour t, kW/m; τ – the time step (1 hour); L_{WPP} – the length of WPP, m; k – the flow average utilization factor; C_t – the predicted market price of electricity at hour t, (€/kWh).

In order to calculate NPV, it is necessary to describe changes in processes for many years ahead. This task leads to uncertainty and necessitates the use of the methods of the theory of stochastic processes. In our case, we assume that electricity prices can be forecast by using the Fourier series and white noise. It should be pointed out that the approach we use is only one of the possible approaches. The proof of its satisfactory accuracy and a more detailed description is given in our previous work [33]. 1.5 % increase in the annual average price is assumed. Moreover, the rated specific wave power is estimated for one year and does not change during the planning period.

B. The Methodology of Feasibility Studies

In general, energy planning issues are formulated in the form of profit maximization tasks. In this paper, we limit ourselves to using only the NPV [34]. The NPV could be formulated as an optimization task as follows:

$$NPV(T_p) \rightarrow max. \quad (10)$$

In our case we estimated two options of NPV:

1. Prosumer takes a credit in bank for WPP construction:

$$NPV(T_p) = -C_{invest} + \sum_{t=1}^{T_P} \frac{(R_t) - \left(\frac{C_{invest}}{T_p} + C_{loan,t} \cdot i_{cred}\right)}{(1 + i_d)^t}, \quad (11)$$

where C_{invest} – initial investments of WPP construction, €; t – the planning year (1, 2, ... T_p=34); $C_{loan,t}$ – the outstanding loan amount of year t, €; i_{cred} – the credit rate, %; i_d – the discount rate, the rate of return that could be earned on an investment in financial markets with a similar risk.

2. Prosumer does not take a loan:

$$NPV(T_p) = -C_{invest} + \sum_{t=1}^{T_p} \frac{R_t}{(1+i_d)^t}. \quad (12)$$

7. CASE STUDY AND RESULTS

A. Input Information

In the case study, we considered wave potential of one sector (with parameters of node point P1 [23] of Latvian EEZ of the Baltic Sea. In this section, the early feasibility study of WPP P1 sector is presented. We estimate the economic criteria of WPS construction, such as NPV of cash flow and PP. Moreover, one of the goals of the study is to determine the coefficient *k*, at which the PP of this project will be 10 years. The NPV is calculated for two alternatives: Alternative 1 presumes taking a loan; Alternative 2 entails no loan. As a result, 42 scenarios are reviewed.

The necessary input parameters and investment cost of P1 sector are displayed in Table 2. It should be mentioned that data of total costs of one set is an assumption.

Table 2

Input Parameters of WPP at Sector P1 of the Baltic Sea

Specific wave power, $P_{rat.max}$, kW/m	Length of WPP, L_{WPP}, m	Costs of hydrokinetic turbine, €/turbine	Number of turbines	Total investments of WPP, M€	Discount rate, %	Credit rate, %
7.67	19 400	15 000	2 156	32.33	4.0	2.6

Costs of one turbine were calculated on the basis of generators as a comparison with common diesel generator price to kW x 3 [35], which appreciate generator underwater working conditions, anchoring/elevating device and network connection. Working hours per year at full capacity in fact should be less because power station will take some shape. Therefore, in respect of *mwd* increase some energy will be shaded.

B. Results

The resulting NPV curves are shown in Figs. 6 and 7.

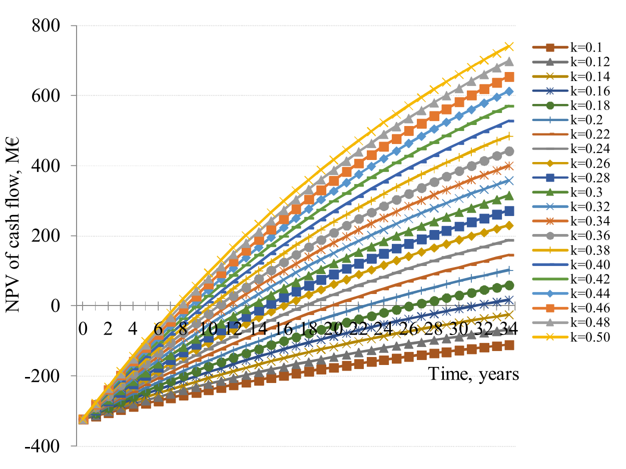

Fig. 6. NPV cash flow of P1 without loan.

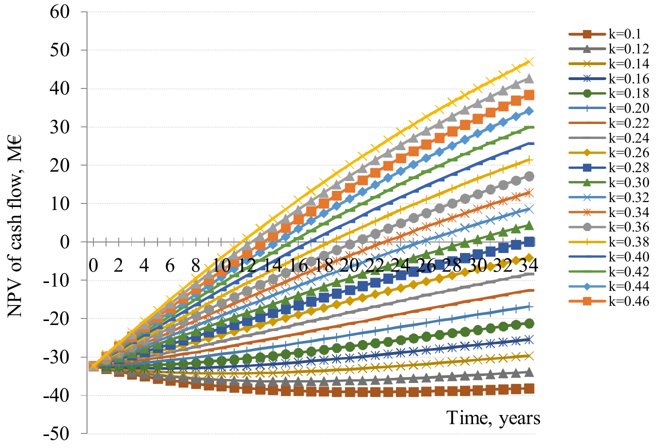

Fig. 7. NPV cash flow of P1 with loan.

Based on the assumptions and reviewed scenarios, the PP of WPP P1 investment varies from 7 years to more than 34 years. Analyzing Alternative 1 of NPV, it is viewed that in order to achieve a plant payback of 10 years, the utilization coefficient should be no less than 0.34. According to the results of Fig. 7, the wave average utilization factor should be more than 0.50.

It is also necessary to take into account that in calculations an average coefficient of wave utilization was adopted. In practice this coefficient will vary constantly depending on the turbine load.

Therefore, one of the objectives of the future research will be to accurately determine the wave utilization factor and its effect on wave energy production and the payback of the wave energy technology.

8. CONCLUSIONS

1. The dynamics of energy consumption and the related climate change are encouraging the increased use of renewable resources.
2. Free surface gravity waves could become an important source of renewable energy.
3. Wave potential is being studied in the world, including the Baltic Sea.
4. The recommendations of binding standards should be more respected in order to assess the potential of waves more precisely.
5. More than 1,000 patents are registered worldwide for wave transformation.
6. The vertical axis turbine operates under laboratory conditions.
7. More accurate economic calculations require input from higher TRL and power plant sketch designs.
8. In order to achieve a payback time of 26 years without a credit in the Baltic Sea power plant with nodal point P1 parameters, the turbine must have the flow utilization factor of 0.18.

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REFERENCES

1. Real Time World Statistic. (n.d.). Available at https://www.worldometers.info/world-population/
2. World Energy Consumption Since 1820 in Charts. (n.d.). Available at https://ourfiniteworld.com/2012/03/12/world-energy-consumption-since-1820-in-charts/
3. Renewable Energy Statistics. (n.d.). Available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics#Renewable_energy_produced_in_the_EU_increased_by_two_thirds_in_2007-2017
4. Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the reģions: Energy 2020. A strategy for competitive, sustainable and secure energy [COM(2010)639]. Available at https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2020-energy-strategy.
5. Global Energy & CO2 Status Report (2018). *The Latest Trends in Energy and Emissions in 2018*. Available at https://www.iea.org/geco/emissions/.
6. NASA Earth Observatory. (n.d.). Available at https://earthobservatory.nasa.gov/world-of-change/DecadalTemp
7. Tapio, P., Varho, V., & Heino, H. (2013). Renewable Energy in the Baltic Sea Region 2025. *Journal of East-West Business*, *19*, 47–62. 10.1080/10669868.2013.779544.
8. Thomas, J., Barve, K.H., Dwarakish, G., & Ranganath, L. (2015). A Review on Assessment of Wave Energy Potential. In *National Conference on Futuristic Technology in Civil Engineering for Sustainable Development* (178–186), 9 May 2015, Department of Civil Engineering, SJBIT.
9. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S. ....& von Stechow, C (2010). Special Report of the Intergovernmental Panel on Climate Change IPPC. *Renewable Energy Sources and Climate Change Mitigation.* United Kingdom and New York: Cambridge University Press.
10. ETIPOCEAN (n.d.). *Ocean Energy Statistics 2018: Europe Leading the Sector*. Available at https://www.etipocean.eu/news/ocean-energy-statistics-2019/
11. IRENA (2014). *Wave Energy: Technology Brief*. Available at https://www.irena.org/publications/2014/Jun/Wave-energy
12. Rusu, E., & Onea, F. (2018). A Review of the Technologies for Wave Energy Extraction. *Clean Energy*, *1*. 10.1093/ce/zky003.
13. Magagna, D., & Uihlein, A. (2015). Ocean Energy Development in Europe: Current

Status and Future Perspectives. *International Journal of Marine Energy*, 11, 84–104. https://doi.org/10.1016/j.ijome.2015.05.001.

14. Melo AB (2010). *Pico Power Plant: Perspectives for the Future?* Available at http://www.picoowc.net/files/33/new3_84d9ee44e457ddef7f2c4f25dc8fa865.pdf.
15. Ocean Energy Systems (2016). *Annual Report Ocean Energy Systems 2016*. Available at https://report2016.ocean-energy-systems.org/
16. ETIPOCEAN (n.d.). *EU-funded Ocean Energy Projects Framework Programme 7 & Horizon2020*. Available at https://www.etipocean.eu/assets/Uploads/170418-EU-funded-projects.pdf
17. Ingmarsson, P., & Hüffmeier, J. (2019). *2030 and 2050 Baltic Sea Energy Scenarios – Ocean Energy*. RISE Research Institutes of Sweden, Swedish Agency for Marine and Water Management.
18. Soomere, T., & Eelsalu, M. (2014). On the Wave Energy Potential along the Eastern Baltic Sea coast. *Renewable Energy: An International Journal*, *71*, 221–233.
19. Mørk, G., Barstow, S., Kabuth, A., & Pontes, M. (2010). Assessing the Global Wave Energy Potential. In *ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering*. Shanghai, China. 3. 10.1115/OMAE2010-20473.
20. European Commission (n.d.). *EU Strategy for the Baltic Sea Region*. Available at https://ec.europa.eu/regional_policy/lv/policy/cooperation/macro-regional-strategies/baltic-sea/
21. Avotiņš, A., Greivulis, J., & Kalniņš, L. (2008). Baltijas jūras potenciāls viļņa enerģijas pārveidošanai. *Enerģētika un elektrotehnika*, *23*, 213–224.
22. Jakabson, P. (2011). *Mapping and Assessment of the United States Ocean*. Wave Energy Electric Power Research Institute, Technical report.
23. Beriņš, J., Beriņš, J., & Kalnačs, A. (2016). Wave Energy Potential in the Latvian EEZ. *Latvian Journal of Physics and Technical Sciences*, *3*, 22–23.
24. Radziņš, Z., & Zars, V. (1964). Hidrauliskās mašīnas un mehānismi. *Latvijas Valsts izdevniecība*.
25. National Date Buoy Centre (n.d.). Measurement Description and Units. Available at http://www.ndbc.noaa.gov/measdes.shtml
26. MK noteikumi. Nr.779 (17.08.2010.). Noteikumi par bāzes līniju punktu koordinātēm.
27. Beriņš, J. (2019). *Ocean and Marine Energy Options and Development*. Doctoral Thesis. Available at https://ortus.rtu.lv/science/lv/publications/29289
28. Beriņš, J., & Beriņš, J. (2017). New Hydrokinetic Turbine for Free Surface Gravitational Wave Transformation. *Latvian Journal of Physics and Technical Sciences*, *6*, 32–41.
29. Betz, A. (1966). *Introduction to the theory of flow machines*. NY: Pergamon Press.
30. Powell, W. B., & Miesel, S. (2018). Tutorial on Stochastic Optimisation in Energy-Part II: An Energy Storage Illustration. *IEEE Trans. Power Syst.*, *31*(2), 1468–1475.
31. Petrichenko, R., Baltputnis, K., Sauhats, A., & Soboļevskis, D. (2017). District Heating Demand Short-Term Forecasting. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe),* (pp. 1374–1378). 6–9 June 2017, Italy, Milan. 10.1109/EEEIC.2017.7977633.
32. Sauhats, A., Petrichenko, R., Broka, Z., Baltputnis, K., & Soboļevskis, D. (2016). ANN-Based Forecasting of Hydropower Reservoir Inflow. In *57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2016)*, 13–14 October 2016, Latvia, Riga. 10.1109/RTUCON.2016.7763129. Electronic ISBN: 978-1-5090-3731-5, USB ISBN: 978-1-5090-3730-8

33. Petrichenko, Ļ., Sauhats, A., Petričenko, R., & Bezrukovs, D. (2018). Long-Term Price Forecasting for the Cost-Benefit Analysis of Power Equipment. In *59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University*, 12–14 November 2018, Latvia, Riga. 10.1109/RTUCON.2018.8659888. Electronic ISBN: 978-1-5386-6903-7, USB ISBN: 978-1-5386-6902-0
34. Sauhats, A., Zemīte, L., Petrichenko, Ļ., Moškins, I., & Jasevičs, A. (2018). Estimating the Economic Impacts of Net Metering Schemes for Residential PV Systems with Profiling of Power Demand, Generation, and Market Prices. *Energies*, *11*(11), 1–19. 10.3390/en11113222.
35. Energolukss (n.d.). *Generators*. Available at https://www.energolukss.lv/shop/product/generators-sdmo-diesel-15000-te-xl-c-10kw-riteni-9349?category=8.

PRIEKŠIZPĒTES STADIJAS EKONOMISKAIS NOVĒRTĒJUMS VIĻŅU SPĒKSTACIJAI BALTIJAS JŪRĀ

J. Beriņš, Ļ. Petričenko

Kopsavilkums

Šis raksts ir par vienu no alternatīvajiem enerģijas avotiem – brīvas virsmas gravitācijas viļņiem un to izmantošanu. Par galvenajiem enerģijas izmantošanas ietekmes faktoriem tiek uzskatīts viļņu potenciāls un tā pārveidošanas ierīču efektivitāte. Darba mērķi ir sekojoši: viļņu potenciāla novērtēšana, enerģijas pārveidošanas modeļa un turbīnas izvēle, kā arī ekonomisko kritēriju izvirzīšana, ņemot vērā viļņu un cenu mainīgumu. Rakstā iekļauts arī minētās turbīnu elektrostacijas izmaksu teorētiskā novērtējuma apraksts.

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PARAFFIN PERMEABILITY OF SYNTHETIC GYPSUM BINDERS MODIFIED BY INDIVIDUAL POLYMERS

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The paper presents an experimental study of five different gypsum composites taking into account paraffin permeability. The composites consist of synthetic gypsum, paraffin and polymers. The samples were produced from gypsum slurry of mixing ingredients, all in the liquid state. After 7 days of maturing, the condition of the samples was assessed as well as drying time was determined. In the second part, the paraffin tightness of different samples was analysed. The results showed that after three weeks of tests the tightness sample was A4. Other polymers were characterised by lower tightness. The content of polymer had also the effect on the final results, but the direct relation between polymer content and paraffin tightness was not observed.

Keywords: *admixture, gypsum, polymer, phase change materials, tightness*

1. INTRODUCTION

The synthetic gypsum products are commonly used in the building industry [1]. The production of gypsum lies in the conversion of calcium carbonate in flue gas desulfurization technology using a wet limestone method that is often integrated with coal combustion in power plants [2]. Some power production in a European country, like Poland or Germany, is still based on coal burning. Therefore, in such cases the direct production of gypsum elements on site (in the factory located nearby) is possible. Even the gypsum application in the construction sector is widely known for 5000 years [3], the contemporary products are often modified to achieve better thermophysical properties. There are two main chemical compounds, which have been widely investigated and tested over recent decades: water-soluble polymers and phase change materials.

The main goal of using polymers in gypsum slurry is the modification of setting process, which involves gypsum hydration/crystallization and final structure of gypsum matrix [4]. Based on the application in cements, Pouches revealed that polymers had the considerable influence on hydration delay [5]. Bülichen [6] and Patural [7] showed that HEMC improved water retention of cement and gypsum. Moreover, the influence of Tylose MH1000 content on gypsum thermal conductivity was also confirmed [8]. On the other hand, to increase the durability of cementitious composites, various internal curing agents, including superabsorbent polymers (SAPs), are often used [9]. In gypsum polymers, the porosity, pore-structure, water retention and mechanical properties change considerably [10]. The effect of microstructure on moisture diffusivity in cement mortars was determined by Garbalińska et al. [11], [12].

The incorporation of different types of phase change materials in gypsum plaster or wallboard leads to a considerable increase in their thermal inertia [13]. The first investigated technology based on the direct application of fatty acids in gypsum slurry [14], [15] or paraffin [16], [17] suffers from the leakage problems [18]. Newly emerging materials containing phase-change materials are based on micro-encapsulation of paraffin. The idea of this solution is the placement of paraffin in a special capsule, small spheres that keep the material in the stable form under all conditions [19], [20], [21]. Such acrylic microcapsules can be directly incorporated into a gypsum product. However, the total volume of pure PCM closed inside the capsules is relatively low in comparison with the total volume. Moreover, this solution is very expensive to use due to the production cost of microcapsules, which disqualifies large-scale use of phase-change material.

The main goal of the present study is to improve the existing technology by increasing the tightness using a polymer. In the experimental analysis, the paraffin was used as a phase change material, mixed with gypsum slurry modified by five types of polymers. The commercially available paraffin, RT25, was widely used in past for building product application: opaque – [22] or transparent [23]. The main advantages of paraffin are primarily the large heat capacity so that it allows accumulating heat. However, it should be mentioned that the use of paraffin has, unfortunately, many negative effects on buildings. One and the most dangerous is its flammability. Another disadvantage is undoubtedly the reduction of the strength of the final product. Some research was devoted to the application of fibre and plasticizer [24]. The last disadvantage from the perspective of paraffin application in building layers is low thermal conductivity, which is of great importance in the case of heat transfer [25].

The objective of the present research is to determine which polymer gives the best results in terms of permeability of paraffin through a gypsum composite. This is extremely important in the case of the application of a layer, in which paraffin is contained. The leakage of paraffin when it is in a liquid state is unacceptable. Another quite important feature of such an application is the avoidance of a very expensive process which is micro-encapsulation. The process consists in closing the phase-change material in small capsules, which means that there is no leakage outside. The idea behind the research is to check whether the use of selected polymers in a mixture of gypsum and paraffin will bring tangible results of maintaining the paraffin inside the mixture.

2. MATERIAL SELECTION

The materials used in this study are four polymers from group A and one polymer from group B, in different proportions. The group A is characterised by the use as a binder in deeply penetrating and universal soils for various substrates, e.g., made of concrete, bricks, plasterboard, gypsum plaster, while the group B creates a different structure on the paint surface, resulting in superior durability and performance. The emulsion is built from an organic, pure acrylic polymer and an inorganic SiO2-phase. The used paraffin was RT25 produced by Rubitherm. RT25 is characterised by a melting point between 16–31°C, with a peak latent heat at 25°C. Total heat storage capacity is 210 kJ/kg. Heat conductivity is 0.2 W/(m·K). The gypsum used for the sample preparation was produced using the wet limestone method in the brown coal power plant. More information about the used polymers is listed below and compared in Table 1.

A1 – Polymer used mainly as a binder for the production of decorative and protective external coatings resistant to changing weather conditions. It is a polymer used in universal soils. pH 8.0–8.5. Dry matter content 50 ± 1 %.

A2 – Vinyl-male copolymer, a binder in internal paints, in masses and decorative plasters. pH 3.5–5. Content of dry substance 50 ± 2 %.

A3 – Polymer with high flexibility and adhesion to the substrate. pH 4.0–6.0. Dry substance content 49 ± 1 %.

A4 – Designed for forming protective and decorative coatings for mineral surfaces, especially for mosaic plasters.

B1 – Polymer used in paints due to its construction and composition based on pure acrylic polymer allows for the creation of a nanocoating, which is characterised by high fire resistance.

Table 1

Types and Properties of Polymers Used in the Experiment

	A1	A2	A3	A4	B1
Application	Universal cover	Inks in the interior	Binder for the substrate	Impregnate for brick and stone	Emulsion
pH	8.0-8.5	3.5÷5.0	4.0÷6.0	7.5÷8.5	No data
Dry content substance [%]	50±1	50±2	49±1	50±1	45
MTTF* [°C]	8÷12	4÷6	0	13÷19	7
T_g** [°C]	18÷22	18÷20	-2÷0	22	12

* – minimum film forming temperature ** – glass transition temperature

3. SAMPLE PREPARATION

In the presented study, the samples were prepared using silicone molds and containers with a capacity of 100 ml. The order in which the components were introduced was as follows. In the beginning, the plaster was weighed and added first to the container. The appropriate amount of water was then measured and mixed until suitable consistency was obtained. Then a measured amount of paraffin was introduced and the polymer was added and everything was mixed for about 15 seconds. The order concerned both silicone molds and containers, with the right proportions for each option. At the initial phase of testing, it was checked whether it was possible to mix the polymer together with gypsum and paraffin. Suitable silicone molds were used that allowed making samples with a mass of 500 g. Based on the literature review, it was found that the most effective ratio of paraffin to gypsum was 0.2 : 1. Samples were made for each polymer with different percentages: 0.5 %, 1.0 %, 2.0 %, 3.0 %, 5.0 % and 10.0 %. Subsequently, samples of the mixture of gypsum and polymer were made in the same polymer content excluding samples of 5.0 % and 10.0 %. The paraffin was then poured onto the surface of the dried material.

Fig. 1. Gypsum product sample (500 g) in silicon form to determine the mixing possibilities of gypsum, polymer and paraffin.

4. INITIAL RESULTS – MATURING OF COMPOSITES

In the present study, the drying time was determined on the basis of organoleptic sensations. As a result of drying the material, an indicator was introduced, which after pressing the mixture showed whether the material had already dried or not. Examination of the possibility of mixing the polymer together with paraffin and gypsum took two weeks during which 500 g samples were made and then the drying process was observed. In some samples, especially with contents of 5 % and 10 %, the polymer leaked onto the gypsum surface. In another case, using the polymer A3, after the mixture dried, it shrank and then broke down, which directly eliminated this polymer from further tests.

On the basis of the conducted research, the drying time for individual polymers was evaluated in several ranges. As can be seen in each case, the increase in the proportion of polymers also increased the drying time. For the A3 polymer, it was not possible to determine the drying time unambiguously, so no graph showing the drying process was made. The graphs presented in Fig. 4 show the drying time depending on the proportion of polymer.

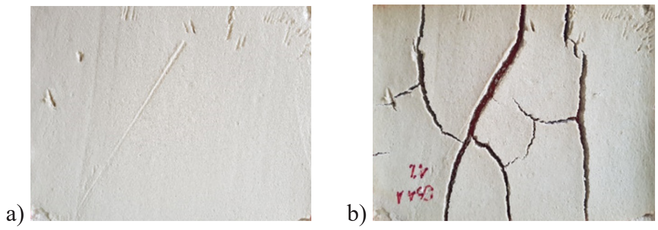

Fig. 2. Gypsum plaster with 1 % of polymer (A3) and paraffin,
a) before drying, b) after weekly drying.

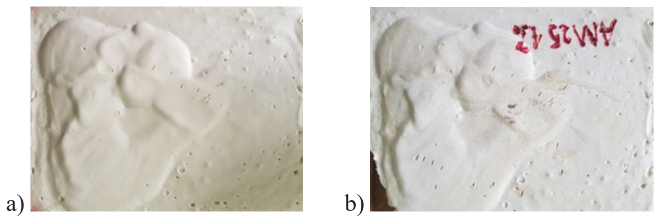

Fig. 3. The best sample with the A4 polymer
a) before drying b) after drying.

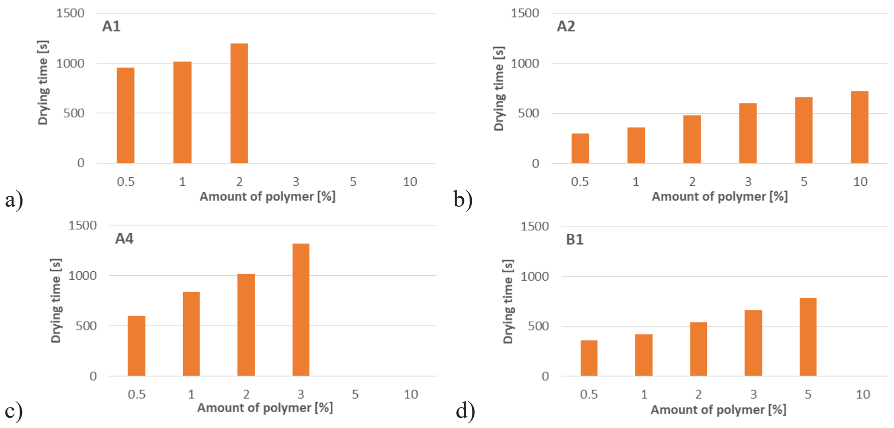

Fig. 4. Drying time for gypsum slurry with paraffin and different polymer mixtures
a) A1, b) A2, c) A4, d) B1.

Analysing the graphs in Fig. 4, it can be concluded that the best polymers in terms of drying time are A2 and B1. In both cases, the lowest proportion of polymer gave a result of about 360 seconds, and the highest value, i.e., 10 %, did not exceed 720 seconds. Unfortunately, in both cases, the drying speed was the only advantage of application in the building layer because, as it was shown in paragraph 5, both polymers did not keep the paraffin inside in the period of three weeks.

5. PARAFFIN PERMEABILITY

Another test to determine the suitability of the mixture for use as a building layer was to prepare samples in 100 ml cylinder vessels with a diameter of 57 mm, after which the mixture was allowed to dry for a week. To carry out this test, the cups were specially prepared by making several holes on the bottom. At the beginning of the test, the holes were sealed and the gypsum slurry was produced according to the receipt provided in Section 3. The next step was to expose the holes made at the bottom of the samples. Then paraffin was poured onto the top of the sample so that the paraffin could pass through the samples and flow out through the exposed holes. Thanks to this step, it was easy to check whether a given polymer improved the paraffin tightness. In each case, the same amount of gypsum and polymer mixture was applied to each cylinder cup equal on the high of 20 mm. Each sample contained the same volume of paraffin equal to 1140 mm^3. Due to the fact that each polymer interacts differently with gypsum, a various value was obtained in the drying process.

Table 2

The Amount of Gypsum Mixture with the Polymer after a Week of Drying

Polymer type	Content of polymer, %			
	0.5	1.0	2.0	3.0
A1	12	15	15	15
A2	23	23	20	15
A3	18	17	15	17
A4	17	15	12	11
B1	20	22	22	22

Analysing the results presented in Table 2, it can be seen that the proportion of polymer in each case gave different results. Polymers such as A1 and A4 reduced the amount of the mixture compared to the sample before drying. On the other hand, the polymer A2 showed that the mixture increased in volume compared to the initial state. The situation was similar for the polymer B1.

As mentioned before, the samples were left for a week to mature and dry properly. Thanks to this form of the mixture, paraffin was poured in for further testing. In each sample, it was introduced in the same amount of paraffin (20 mm of liquids on the gypsum). The paraffin level was checked at intervals of 7 days after pouring paraffin on the surface of the gypsum in the containers.

Analysing Fig. 5, it can be seen that the smallest loss of paraffin was noted by the A4 polymer, which in a 3-week interval lost only 2 mm in the case of a 0.5 % share and the same in the share of 2.0 %. The largest changes in the amount of paraffin were recorded in both 2.0 % and 3.0 %. The major changes were noted for polymer A3, in which each share after 3 weeks allowed for a total loss of paraffin.

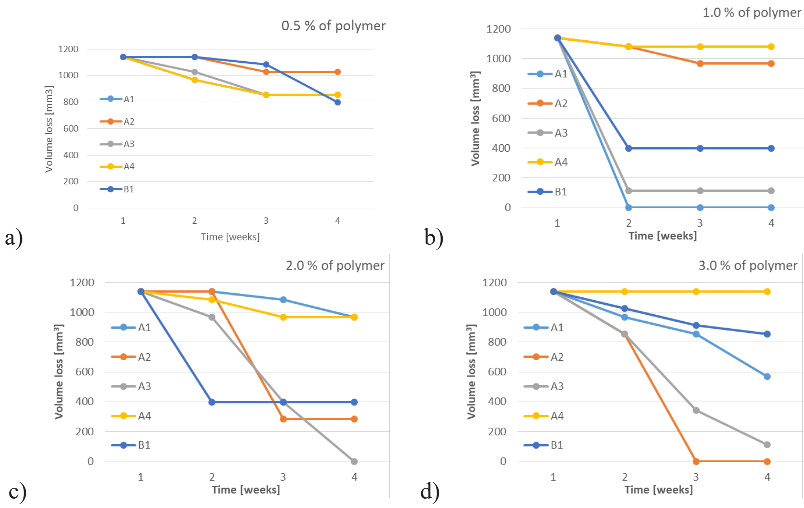

Fig. 5. Paraffin permeability after 3 weeks from the time it was applied to the surface of a sample of gypsum and polymer a) with a 0.5 % share, b) with a 1.0 % share, c) with a 2.0 % share, d) with a 3.0 % share.

As mentioned before, the samples with 5.0 % and 10.0 % share were not taken into account because in each of the samples the results did not give satisfactory outcomes. This was mainly due to the fact that the polymer content was too high, which did not combine with the mixture of gypsum and paraffin, and a large part of it was not inbuilt but remained on the surface of the sample until it evaporated.

6. CONCLUSIONS

As a result of research on a mixture of plaster, paraffin and polymers, several conclusions can be drawn. First of all, it has been confirmed that the polymer has an unequivocal effect on the properties of gypsum product. In one case, it causes excess gypsum foaming, but in the other case polymer does not combine with the mixture in 100 %. Another relatively important feature that has been revealed during the addition of the polymer is the extension of the drying time of the mixture. However, the most important feature that reveals during the addition of the polymer is the decrease in the strength of gypsum. The structure of the mixture in several samples led to gypsum cracking already after drying, and most of the samples were damaged during demoulding.

Analysing the second part of the research, some additional conclusions can be drawn. Based on the tests carried out, it can be observed that the volume of gypsum contained a different proportion of polymers. At the same volume in each sample, after a week of drying, it turned out that in some samples the volume exceeded the initial state. Therefore, based on the results of leakage experiments the best polymer that was used in this study was A4. Choosing the A4 polymer was mainly guided by the smallest losses resulting from the passage of paraffin through the structure. Therefore, the A4 polymer gave the best results in terms of paraffin permeability. It can be seen that, when compared to the second permeability of the B1 polymer, the fluctuations were definitely greater, especially at 1 % and 2 % of the polymer. However, the A4 polymer in each of the four shares did not give an unambiguous answer how much percentage of the polymer was the best. 0.5 %, 1.0 % and 2.0 % showed slight fluctuations compared to 3.0 % where there were no fluctuations. On this basis, it is not possible to clearly indicate which percentage gives the best results. In order to know the next properties of this polymer, further tests are necessary, mainly strength tests as well as seasoning of samples containing polymers and phase change material all together. To confirm the operation of a mixture of gypsum, polymer and paraffin, real-scale tests under all-year atmospheric conditions seem necessary.

REFERENCES

1. Lushnikova, N., & Dvorkin, L. (2016). Sustainability of gypsum products as a construction material. In J. Khatib, ed., *Woodhead Publishing Series in Civil and Structural Engineering* (pp. 643–681). https://doi.org/https://doi.org/10.1016/B978-0-08-100370-1.00025-1
2. Cheremisinoff, N. P. (2012). Solid wastes. In *Handbook of Pollution Prevention and Cleaner Production* (pp. 31–61). https://doi.org/10.1016/b978-1-4377-7815-1.00002-3
3. Felsing, W. A., & Potter, A. D. (1930). Gypsum and Gypsum Products. *Journal of Chemical Education*, *7*(12), 2788. https://doi.org/10.1021/ed007p2788
4. Mróz, P., & Mucha, M. (2018). Hydroxyethyl Methyl Cellulose as a Modifier of Gypsum Properties. *Journal of Thermal Analysis and Calorimetry*, *134*(2), 1083–1089. https://doi.org/10.1007/s10973-018-7238-3
5. Pourchez, J., Peschard, A., Grosseau, P., Guyonnet, R., Guilhot, B., & Vallée, F. (2006). HPMC and HEMC Influence on Cement Hydration. *Cement and Concrete Research*, *36*(2), 288–294. https://doi.org/10.1016/j.cemconres.2005.08.003
6. Bülichen, D., Kainz, J., & Plank, J. (2012). Working Mechanism of Methyl Hydroxyethyl Cellulose (MHEC) as Water Retention Agent. *Cement and Concrete Research*, *42*(7), 953–959. https://doi.org/10.1016/j.cemconres.2012.03.016
7. Patural, L., Marchal, P., Govin, A., Grosseau, P., Ruot, B., & Devès, O. (2011). Cellulose Ethers Influence on Water Retention and Consistency in Cement-Based Mortars. *Cement and Concrete Research*, *41*(1), 46–55. https://doi.org/10.1016/j.cemconres.2010.09.004
8. Heim, D., Mrowiec, A., Pralat, K., & Mucha, M. (2018). Influence of Tylose MH1000 Content on Gypsum Thermal Conductivity. *Journal of Materials in Civil Engineering*, *30*(3). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002177
9. Almeida, R. F. C., & Klemm, A. J. (2018). Effect of GGBS on Water Absorption Capacity and Stability of Superabsorbent Polymers Partially Crosslinked with Alkalis. *Journal of Materials in Civil Engineering*, *30*(12), 4018315. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002511
10. Singh, M., & Garg, M. (1996). Relationship between Mechanical Properties and Porosity of Water-Resistant Gypsum Binder. *Cement and Concrete Research*, *26*(3), 449–456. https://doi.org/10.1016/S0008-8846(96)85032-0
11. Garbalińska, H., Kowalski, S. J., & Staszak, M. (2013). Moisture Diffusivity in Mortars of Different Water-Cement Ratios and in Narrow Ranges of Air Humidity Changes. *International Journal of Heat and Mass Transfer*, *56*(1–2), 212–222. https://doi.org/10.1016/j.ijheatmasstransfer.2012.09.026

12. Garbalińska, H., & Wygocka, A. (2014). Microstructure Modification of Cement Mortars: Effect on Capillarity and Frost-Resistance. *Construction and Building Materials*, *51*, 258–266. https://doi.org/10.1016/j.conbuildmat.2013.10.091
13. Hawes, D. W., Feldman, D., & Banu, D. (1993). Latent Heat Storage in Building Materials. *Energy and Buildings*, *20*(1), 77–86. https://doi.org/10.1016/0378-7788(93)90040-2
14. Feldman, D., Banu, D., & Hawes, D. W. (1995). Development and Application of Organic Phase Change Mixtures in Thermal Storage Gypsum Wallboard. *Solar Energy Materials and Solar Cells*, *36*(2), 147–157. https://doi.org/10.1016/0927-0248(94)00168-R
15. Stovall, T. K., & Tomlinson, J. J. (1995). What are the Potential Benefits of Including Latent Storage in Common Wallboard? *Journal of Solar Energy Engineering*, *117*(4), 318–325. Retrieved from http://dx.doi.org/10.1115/1.2847868
16. Feldman, D., Shapiro, M. M., Banu, D., & Fuks, C. J. (1989). Fatty Acids and their Mixtures as Phase-Change Materials for Thermal Energy Storage. *Solar Energy Materials*, *18*(3–4), 201–216. https://doi.org/10.1016/0165-1633(89)90054-3
17. Peippo, K., Kauranen, P., & Lund, P. D. (1991). A Multicomponent PCM Wall Optimized for Passive Solar Heating. *Energy and Buildings*, *17*(4), 259–270. https://doi.org/10.1016/0378-7788(91)90009-R
18. Kośny, J. (2015). Chapter 2: Short history of PCM applications in building envelopes. In *PCM-Enhanced Building Components* (p. 281). https://doi.org/10.1007/978-3-319-14286-9
19. Jurkowska, M., & Szczygieł, I. (2016). Review on Properties of Microencapsulated Phase Change Materials Slurries (mPCMS). *Applied Thermal Engineering*, *98*, 365–373. https://doi.org/10.1016/j.applthermaleng.2015.12.051
20. Konuklu, Y., Ostry, M., Paksoy, H. O., & Charvat, P. (2015). Review on Using Microencapsulated Phase Change Materials (PCM) in Building Applications. *Energy and Buildings*, *106*, 134–155. https://doi.org/10.1016/j.enbuild.2015.07.019
21. Li, C., Yu, H., Song, Y., & Liu, Z. (2019). Novel Hybrid Microencapsulated Phase Change Materials Incorporated Wallboard for Year-Long Year Energy Storage in Buildings. *Energy Conversion and Management*, *183*, 791–802. https://doi.org/10.1016/J.ENCONMAN.2019.01.036
22. Halimov, A., Lauster, M., & Müller, D. (2019). Validation and Integration of a Latent Heat Storage Model into Building Envelopes of a High-Order Building Model for Modelica Library AixLib. *Energy and Buildings*, *202*, 109336. https://doi.org/10.1016/J.ENBUILD.2019.109336
23. Gowreesunker, B. L., Stankovic, S. B., Tassou, S. A., & Kyriacou, P. A. (2013). Experimental and Numerical Investigations of the Optical and Thermal Aspects of a PCM-Glazed Unit. *Energy and Buildings*, *61*, 239–249. https://doi.org/10.1016/j.enbuild.2013.02.032
24. Oliver, A. (2012, May 1). Thermal Characterization of Gypsum Boards with PCM Included: Thermal Energy Storage in Buildings through Latent Heat. *Energy and Buildings*, *48*, 1–7. https://doi.org/10.1016/j.enbuild.2012.01.026
25. Wang, X., Yu, H., Li, L., & Zhao, M. (2016). Research on Temperature Dependent Effective Thermal Conductivity of Composite-Phase Change Materials (PCMs) Wall Based on Steady-State Method in a Thermal Chamber. *Energy and Buildings*, *126*, 408–414. https://doi.org/10.1016/j.enbuild.2016.05.058

INDIVIDUĀLU POLIMĒRU PĀRVEIDOTĀ SINTĒTISKĀ ĢIPŠA SAVIENOJUMU PARAFINA CAURLAIDĪBA

K. Povala, D. Heims

K o p s a v i l k u m s

Rakstā aprakstīti piecu dažādu ģipša kompozītu eksperimentālie pētījumi, ņemot vērā parafīna caurlaidību. Kompozīti izgatavoti no sintētiska ģipša, parafīna un polimēriem. Paraugi tika izgatavoti no ģipša suspensijas, kas sastāv no viegli sajaucamām sastāvdaļām šķidrā stāvoklī. Pēc 7 dienu nogatavināšanas tika novērtēts paraugu stāvoklis un noteikts žāvēšanas laiks. Pētījumā otrajā daļā tika analizēta dažādu paraugu necaurlaidība. Rezultāti liecina, ka pēc trīs nedēļu testiem paraugam A4 bija lielāka necaurlaidība. Citiem polimēriem raksturīga zemāka necaurlaidība. Polimēru saturs ietekmē arī galīgos rezultātus, tomēr tieša saistība starp polimēra saturu un parafīna necaurlaidību netika novērota.

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ENSURING RELIABILITY OF CONTROL DATA IN ENGINEERING SYSTEMS

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The paper presents the approach of determination of rationality coefficients of control system, inputted uncertainty, control of the process, system errors, and uncertainty. Algorithms for identifying the states of system have been developed on the basis of theorems of identification. They actually implement the theoretical multiplication cross-section and establish that increasing the reliability of information is possible only through the use of redundancy (structural, procedural, and informational). The increase in the reliability of control data with the developed methods ensures significant improvement of the functioning of information systems and facilitates the adoption of more substantiated decision making.

Keywords: *control data, engineering system, reliability, theorems of identification, uncertainty*

1 INTRODUCTION

Modern automated control systems, i.e., systems designed to collect, analyse, evaluate, update, and display information relevant to the engineering problem, are adaptive systems that are able to change their structure and data processing technology in order to maximise the reliability of the results. The tasks of monitoring, analysing and improving the reliability of such a system can be reduced to the following functions: identification, evaluation, and measurement.

The need to identify the structure and status of the engineering system as a whole, as well as its separate subsystems, is due to the fact that the system and its components are exposed to external random interference that may interfere with the structure of the system or cause changes in the structure of the messages. The first and the second entails, as a rule, change in the degree of reliability of information processing results. The identification function implies the implementation of the whole spectrum of control procedures and the analysis of their results for revealing the essential features against the background of nonessential details; the elaboration of a more complex and detailed description of the information process, the phenomenon to a simple reference (alternative); registration of properties of the controlled process; checking the statistical hypothesis.

2. PROBLEMS OF CONTROL DATA RELIABILITY

Methods for assessing the state of the process are implemented selectively and unsystematically, which do not allow obtaining a sufficiently high guarantee of the received data conformity with the requirements of existing standards [1], [2]. This, in turn, leads to an inadequate response to changes in indicators in the functioning of the engineering system, as well as to an unreliable forecast of their further development.

Process control and analysis involve managing processes based on the compilation of heuristics with the definition of strata, the set of states, the calculation of possible states, the degree of their feasibility and the likely consequences of this implementation; the definition of the growth of the Euclidean distance between the pairs of real states that are observed and are adjacent to each other at a certain time interval, as well as the probability and possibility of such a transition and the driving forces that cause it [3]–[9].

As it is asserted in [2], it is impossible to consider information without taking into account any situation of uncertainty. Validation of reliability is based on the information obtained during the identification. Its task is to work out quantitative indicators of data reliability.

Changing the structure of the engineering system and technology of data collection and processing, based on the results of identification and evaluation, aims at optimising the operating modes of the information system in the specific circumstances that have developed and maximising the reliability of its functioning results.

Inadequacy in systems is mainly due to the incompleteness of the original data, the nebulosity (fuzziness) of the information and the limitations of the class of implemented algorithms [3], [4], [10], [11].

The incompleteness of the source data, which is the result of limited observation of objects of control and insufficient information about the factors that affect the processes in the reservoir, means that if there is

$$V(N, f) = (\tilde{f} \in F : N(\tilde{f})) = N(f) \quad (1)$$

the set of all elements $\tilde{f}$ that do not differ from the element f using the information *N*, then the value of *N(f)* does not allow determining which of the sets S($\tilde{f}\xi$), where $\tilde{f} \in V(N, f)$, leads to the desired *ξ*-approximation [10], [12].

The nebulosity (fuzziness) of information resulting from the limited accuracy of measurements and estimates, as well as the presentation and processing of data, failures of equipment, interference in communication channels, drift of equipment parameters and measured parameters, etc., means that if there is

$$V(N_\rho, f) = \{\tilde{f} \in F : N_\rho(f) \in E[N(\tilde{f}), \rho]\} \tag{2}$$

the set of elements *f* for which $N_{\rho(f)}$ can serve as fuzzy (approximate) information and the requirement is fulfilled

$$N_\rho(f) \in E[N(f), \rho] \forall f \in F, \tag{3}$$

where *E* – the operator of information fuzziness, ρ – the measure of fuzzy information, *E[N(f), ρ]* – the set that represents fuzzy information about *f*, ∀ – the universal quantifier that confirms the validity of the equation for any values of the predicate *f*, then only the value of $N_\rho(f)$ does not allow stating which of the sets leads to ξ-approximation.

Limits of the class of admissible algorithms or those algorithms that are implemented to solve a particular task in specific conditions and which, of course, are associated with the duration of the implementation process, stability (perseverance) or correctness of the solution, mean that if

$$Q(h) = \{\varphi(h) : \varphi \in R\} \tag{4}$$

there is a plurality of results of application to $h = N_\rho(f)$ of all algorithms *φ* from class *R* of those implemented algorithms, then the knowledge of only $N_\rho(f)$ does not allow stating which specific (or which) of the algorithms of the set *R* will provide a solution to the problem under acceptable conditions (such that there are real) restrictions. At the same time, the general approach to increasing the reliability of information, if the solution space is not secured either by a norm or by a metric, can be based on the general mathematical theory of optimal reduction of uncertainty.

In case of incompleteness or approximation of the output data, when additional information is required, the required *ξ*-approximation can be found only under the condition of a non-empty intersection of the *ξ* sets, i.e.,

$$A(N, f, \xi) = \bigcap_{\tilde{f} \in V(N,f)} S(\tilde{f}_i, \xi) \neq 0 \tag{5}$$

or

$$A(N, f, \xi) = \min_{\tilde{f} \in V(N,f)} S(\tilde{f}_i, \xi) \neq 0\,. \tag{6}$$

As an example, procedure (5) to increase the reliability of the differentiation of information in the case of incomplete data is given in Fig. 1.

The minimum amount of the required information to solve a specific task with the specified degree of reliability (global radius of information) can be defined as follows. If we accept that

$$\xi_1 \le \xi_2 \Rightarrow A(N,f,\xi_1) \subset A(N,f,\xi_2) \quad (7)$$

and note

$$r(N,f) = \inf\{\xi : A(N,f,\xi) \ne S \quad (8)$$

as a local radius of information, i.e., the least ξ, for which there still exists an element belonging to sets for all that do not differ from *f* using information *N*, then

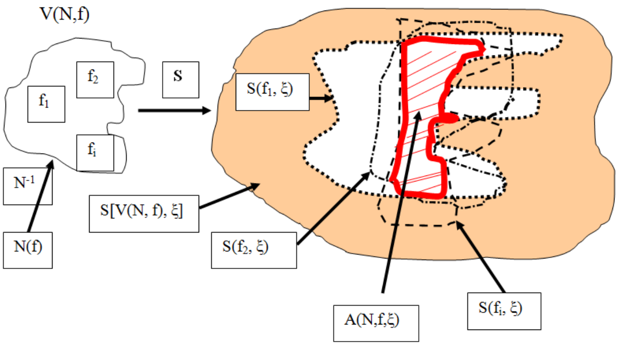

Fig. 1. The scheme of the choice of the set A (N, f, ξ) of all elements that do not differ from the element f using information N (counteraction principle).

the global radius of information may be defined as

$$r(N) = \sup_{f \in F} r(N,f) = \inf\{\xi : A(N,f,\xi), S \forall f \in F\}\,. \quad (9)$$

Then for the exact solution of the problem, i.e., for the case of an unambiguous definition

$$S(\tilde{f}) = S(f) \forall \tilde{f} \in V(N,f)\,, \quad (10)$$

when *S[V(N,f)]* is unique (one and only one),

$$r(N) = \begin{cases} 0, \text{if } S[V(N,f) \text{ is unambiguous for all } f \in F \\ +\infty \quad \text{in opposite case} \end{cases}. \quad (11)$$

Thus, the search for an exact solution to a problem reduces to the definition of the minimum amount of information, the presence of which *r(N)* is converted to zero. However, since the procedures for such a search are often limited to system resources, or too high for additional information, the decision is sought with an error

$$e(\phi, N) = \sup_{f\in F} e(\phi, N, f)(= \inf\{\ \xi : \phi[N(f) \in S(f,\xi)\forall f \in F\}), \tag{12}$$

where $e(\phi, N, f) = \inf\{\xi : \phi[N(f)] \in A(N, f, \xi)\}$ – the local error in the algorithm (procedures) φ from the class of algorithms (procedures) *φ(N)* that use the information *N*, i.e., the least *ξ*, in which the element *φ[N (f)]* belongs to $S(\widetilde{f},\xi)$ for all $\widetilde{f}$ that cannot be distinguished from *f* by using information *N*.

If the variation of the information operator *N* (i.e., the addition of any information that is relevant to the solvable problem) is created, the conditions for choosing the "optimal" information are created. If the information operator *N* can be decomposed into a number of simpler information operators, then the term cardinal *N* is introduced:

$$n = card(N), \tag{13}$$

and the information is non-adaptive if the selection of simpler operators occurs independently (with the help of independent processors) and, accordingly, the information is adaptive if this choice is made consistently, taking into account the results already obtained.

Then the minimum radii of non-adaptive and adaptive information (for the class of algorithms R used in solving the problem) can be represented respectively in the form:

$$\begin{aligned} r^{(i\grave{a})}(R,n) &= \inf_{N\in\varphi^{(i\grave{a})}(n)} r[R(N), N], \\ r^{(\grave{a}\ddot{a})}(R,n) &= \inf_{N\in^{(\grave{a}\ddot{a})}(n)} r[R(N), N], \end{aligned} \tag{14}$$

where

$$\begin{aligned} \varphi^{(i\grave{a})}(n) &= \{N^{(i\grave{a})} : card\,(N^{(i\grave{a})}) \le n\}, \\ \varphi^{(\grave{a}\ddot{a})}(n) &= \{N^{(\grave{a}\ddot{a})} : card\,(N^{(\grave{a}\ddot{a})}) \le n \end{aligned} \tag{15}$$

represent classes of correspondingly non-adaptive and adaptive informational operators of cardinality not higher than *n*. In this case, the information operator *N* only then will become the *n*-th optimal non-adaptive (or adaptive) information (for R) when $N \in \varphi^{(на)}(n)$ either $N \in \varphi^{(ад)}(n)$, $r[R(N), N = r^{(на)}(R,n)$ or $r[R(N), N] = r^{(ад)}(R,n)$.

If approximate information is used

$$N\rho(f) \in E[N(f), \rho]\forall f \in F, \tag{16}$$

where E – the information error operator, ρ – the measure of error information, then the operator N will be the *n*-th optimal non-adaptive (adaptive) approximate information (for ρ, R) if

$$N \in \varphi^{(n-a)}(n) \quad \text{or} \quad N \in \varphi^{(ad)}(n), \tag{17}$$

$$r[R(N_\rho, \mathrm{E}), \mathrm{N}_\rho, \mathrm{E}] = r^{(n-a)}(R, n, \rho) \quad \text{or} \quad r[R(N_\rho, \mathrm{E}), \mathrm{N}_\rho, \mathrm{E}] = r^{(ad)}(R, n, \rho). \tag{18}$$

Here

$$r^{(n-a)}(R, n, \rho) = \inf_{N \in \varphi^{(n-a)}(n)} r[R(N_\rho, \mathrm{E}), \mathrm{N}_\rho, \mathrm{E}], \tag{19}$$

$$r^{(ad)}(R, n, \rho) = \inf_{N \in \varphi^{(ad)}(m)} r[R(N_\rho, E), N_\rho, E] \tag{20}$$

there are n-th minimum radii of non-adaptive and adaptive approximate information (for ρ, R).

Information systems often have to deal with fuzzy (nebulosity) data. The phenomenon of fuzziness (nebulosity) is due, in particular, to the largely incomplete information about objects (processes), when the unknown exact (complex) dependencies are replaced by approximate (simplified) or for the evaluation of the state of the engineering system (partial or complete) mediating parameters, connections, dependencies are applied. Therefore, methods and means of increasing the reliability of information in the conditions of fuzzy (nebulosity) data can be largely distributed to the area of problem solving with incomplete data. If we consider (2) and take into account that $f \in V(N_\rho, f)$, and on the basis of definition (1)

$$V(N, f) = V(N_\rho, f) \subset V(N_\rho, f) \forall f \in F, \tag{21}$$

we can assert that the required ξ-approximation will be found only if the intersection of the set $S(f_i, \xi)$ is not empty, i.e.,

$$A(N_\rho, f, \xi) \bigcap_{\tilde{f} \in V(N_\rho, f)} S(\tilde{f}, \xi) \neq 0. \tag{22}$$

In this case, the global radius of information

$$r(N_\rho) = \sup_{f \in F} r(N_\rho, f) \; (= \inf\{\xi : A(N_\rho, f, \xi) \neq 0 \; \forall f \in F\}), \tag{23}$$

where $r(N_\rho, f) \geq r(N_0, f) = r(N, f) \, \forall f \in F$ – the local radius of the approximate (nebulosity) information and N_0 characterises N under condition $\rho = 0$, i.e., in fact $N_0(f) = N(f)$.

The traditional way of increasing the reliability in this case is to minimise $r(N_\rho)$ or, that is the same, to minimise ρ.

While solving any problem, there are always two issues: solving the problem with the necessary accuracy, and if possible, the cost of this solution, i.e., the resources needed.

An algorithm compiled from a finite number of simple operations may be acceptable for use when achieving the goal set before the system. However, the resources required for its implementation may be such that the decision will lose all meaning: it will be late, will be unstable or incorrect, or costs may be inadequate to the results that will be achieved. Therefore, from the whole set of admissible algorithms ψ(Nρ) that uses information N_ρ, a subset of implemented algorithms is selected, so that any of the algorithms used in the system φ $\varphi : X = \varphi[N_\rho(f)]$ is included in this subset.

Under the conditions of limited class of implemented algorithms, if we consider (4) and take into account that the element *x* obtained as a result of the application of the algorithm $\varphi \in R$ belongs to the set $A(N_\rho, f, \xi) \cap Q(h)$, the ξ-approximation can be found under the conditions of a nonempty intersection of the set

$$A(N_\rho, f, \xi) \cap Q(h) \neq 0 \tag{24}$$

In this case, the global radius of the approximate information (for *R*) will be the minimum value of ξ, for which the set $\psi(\xi)$ has at least one algorithm with *n*, or more precisely the value

$$r(R, N_\rho) = \inf\{\xi : \psi(\xi) \cap R \neq 0\} \tag{25}$$

or

$$r(R, N_\rho) \geq \sup_{f \in F} r(R, N_\rho, f), \tag{26}$$

or

$$r(R, N_\rho, f) = \inf \xi : A(N_\rho, f, \xi) \cap Q[N_\rho(f)] \neq 0 \tag{27}$$

and is the local radius of the approximate information (for *R*).

If there is a set of algorithms

$$R = \phi \in \varphi(N_\rho) : \phi[N_\rho(f)] \in Q[N_\rho(f)] \forall f \in F \ , \tag{28}$$

and $R \subset \overline{R}$, then if $R = \overline{R}$

$$r(R, N_\rho) = \sup_{f \in F} r(R, N_\rho, f) \ , \tag{29}$$

and the algorithm for calculating the ξ-approximation (realisable) for an arbitrary f=F according to the information of N_ρ exists only in the case where $r(R, N\rho) < \xi$ or for $r(R, N\rho) = \xi$, if the error

$$\inf_{\phi \in R} e(\phi, N_\rho) = r(R, N_\rho) \tag{30}$$

is achieved by applying a certain algorithm φ for which the following value can be achieved

$$\inf\{\xi : \phi[N_\rho(f)] \in A(N_\rho, f, \xi) \forall f \in F\}. \tag{31}$$

To evaluate one or another algorithm, a criterion such as complexity can be used. Any algorithm can be represented as a set of primes of simple operations, each of which is characterised by the complexity $comp(p_i)$. The information complexity of the operator $N_\rho(f)$, if there is a calculation program consisting of a finite number of operations $p_1, \ldots, p_k$, can be represented in the form

$$comp[N_\rho(f)] = \sum_{i=1}^{k} comp(p_i). \tag{32}$$

If there is a calculation program $\varphi(y)$ that consists of a finite number of simple operations $q_1, \ldots, q_l$, then the combinatorial complexity of the algorithm $\varphi(y)$ can be expressed as follows:

$$comp[\phi(y)] = \sum_{i=1}^{l} comp(q_i). \tag{33}$$

The complexity of the algorithm φ can be represented as

$$comp(\phi) = \sup_{f \in F}\{comp[N_\rho(f)] + comp[\phi(N_\rho(f))]\}, \tag{34}$$

and the algorithm φ^{oc} that is optimal in complexity with $R(N_\rho, \xi)$ for $R(N_\rho)$ if

$$comp(\phi^{oc}) = comp[R(N_\rho), N_\rho, \xi], \tag{35}$$

where $comp[R(N_\rho), N_\rho, \xi] = \inf\{comp(\phi) : \phi \in R(N_\rho, \xi)\}$ – the ξ-complexity [for $R(N_\rho)$] provided that $inf\psi = +\infty$.

If we accept the φ-class of admissible approximate information operators and present the complexity of the problem as ξ-complexity in the class ψ (for R) in the form

$$comp(R,\varphi,\xi)=\inf_{N_\rho\in\varphi} comp[R(N_\rho),N_\rho,\xi], \tag{36}$$

then the algorithm φ^{oc} will be optimal for complexity in the class ψ (for R) if

$$comp(\phi^{oc})=comp(R,\varphi,\xi), \tag{37}$$

and φ^{oc} uses the approximate information N_ρ with ψ and belongs to $R(N_\rho)$.

The above considerations allow selecting (or constructing) algorithms to be implemented (or rather, the set of such algorithms) at the stage of the technical and operational design of the system. Such algorithms will correspond to specific conditions of its functioning, including for the case of decomposition of the system in case of ensuring the problems of resistance to failures, as well as when changing the dynamics of the engineering system, its overloads, etc.

Algorithms (4)–(7), which actually implement the multiplicative theorem operation, state that increasing the reliability of information is possible only through the use of redundancy (structural, procedural, and informational). In this case, the result can be achieved either under the conditions of simultaneous operation of all sets that are formed by parallel structures on the basis of a standard set of output data (structural redundancy), or during the successive execution of the same procedure over each pair of sets that are formed by one structure on the basis of a standard set of output data (procedural redundancy), or, finally, by combining the first two approaches and using additional structures or procedures that provide the formation of new sets based on all available relevant information (or adjustments already existing), as well as the results of its structuring and other types of processing (information redundancy).

In practice, this means the following:

- the use of a set of devices of the same type, communication channels and (or) data processing means instead of one in the case of structural redundancy;
- the use of multiple identical measurement procedures, data transmission and / or processing instead of one-time procedures, as well as the use of various diagnostic procedures in case of procedural redundancy;
- simultaneous use of several measurement methods (several different types of devices) for measuring the same value, entering test digits during data transmission, using multiple models or data processing algorithms that differ from each other at the conceptual level, taking into account a priori, indirect and concomitant information, as well as background information in the case of adoption of the method of informational redundancy.

It should be noted that in practice there is a combination of the above-mentioned, mutually complementary approaches, improving the quality and efficiency of information systems.

When establishing the apparatus and means of control and analysis of reliability of information on the state of an engineering system, it is very important to justify the choice of specific control methods that take into account the specifics of the object of control, the conditions in which the system operates and the requirements for the object and system.

If we know:

- coefficient of output uncertainty K_{ouc};
- coefficient of control of the process

$$K_{\tilde{N}} = \{\sum_{i=1}^{l} \lambda_i D_i\} / \{\sum_{i=1}^{l} D_i\}, \tag{38}$$

where λ_i – the efficiency coefficient of the i-th control method, which is defined as the ratio of the number of errors A detected to the total number of errors (both detected and those that are not detected) $A + B = \delta$, and D_i – i-th operation of information control;

- total amount of information Q;
- a number of system errors that are not detected, B;
- estimated total coefficient of uncertainty

$$K_{\mathrm{uc}}=[\sum_{i=1}^{l} \frac{\delta_i}{Q} \ \mathrm{Kuc} = (1-\lambda_i) D_i] / (\sum_{i=1}^{l} D_i), \tag{39}$$

or

$$K_{uc} = [\sum_{i=1}^{l} B / Q) D_i] / (\sum_{i=1}^{k} D_i), \tag{40}$$

it is possible to determine the coefficient of rationality of the control system

$$K_{r.c.} = [K_{ouc} (1 - \hat{E}_c) / K_{uc}, \tag{41}$$

which for values K_{rc} <1, i.e., K_{ouc} (1 - K_c) < K_{uc} indicates that the control system is built irrationally or the technology of data processing in the system is not rational.

The choice of conceptual, informational and behavioural models of the control system and verification of their reliability by using “reverse” operations are equally important. This verification may include the following steps (procedures):

- consideration of the design of the model and the feasibility of its development;
- establishing connection of the idea and the feasibility of developing a model with deterministic, randomized and average values of the characteristics of the model;
- research of accepted approximations of real processes;
- consideration of criteria for the effectiveness of parameters and variables;

- research of accepted propositions and hypotheses;
- detecting the connection of the results of the two previous stages with real processes; analysis of the system of disturbing factors and characteristics of the operator; research of the interconnections of all these factors;
- verification of the information and its sources used for model development;
- consideration of the entire control procedure in connection with the definition of the task of the system;
- consideration of the task.

The above-mentioned approach provides reconsideration of the task from a slightly different point of view, which contributes to a deeper and more comprehensive assessment of the system and ultimately allows creating an optimal conceptual model that is adequate to a mathematical model and, as a result, creates conditions for effective control of reliability.

When selecting controlled parameters, their informational value should be considered (separately for the case of operational control of normal modes and separately for emergency control). For operational control, the information value of a parameter can be determined from the expression

$$Z_{ïï} = (\sigma_x / C_x)\ln(\sigma_x / \lambda_x)\rho, \tag{42}$$

and for emergency according to the expression

$$Z_{à} = \frac{\tilde{N}_x}{x_a - m_x} \ln \frac{\sigma_x}{\lambda_x} \rho \quad (\text{for } \xi \geq x_a), \tag{43}$$

where σ_x – the mean square deviation of the parameter ξ; C_x – the maximum rate of change of the parameter ξ in transitional modes; λ_x – the error of the measuring device; ρ – the coefficient that takes into account the distribution of probabilities of values $x \epsilon \xi$; x_a – the minimum value of the parameter ξ, which corresponds to the emergency situation; m_x – the mathematical expectation ξ.

In this case, the generalized characteristic of the information value of the parameter can be represented as

$$Z_n = Z_{on} \cdot Z_a. \tag{44}$$

In addition, the value of information can be expressed through increasing the probability of achieving the goal:

$$I = log\,(p_1/p_0), \tag{45}$$

where p_0 – the probability of achieving the goal before receiving information, and p_1 – the same after receiving the information. Here it is worth noting that if after receiving additional information the probability of achieving the goal is reduced, this indicates the need to move to an alternative strategy. In this sense, the additional information received has a real value, since it saves resources and time by refusing a hopeless strategy.

4. CONCLUSIONS

The algorithms for identifying the states of the engineering system have been developed on the basis of the theorems of identification. They actually implement the theoretical multiplication cross-section and establish that increasing the reliability of information is possible only through the use of redundancy (structural, procedural, and informational).

The above-mentioned approaches to increasing the reliability of control data ensure stable functioning of engineering systems and facilitate the adoption of substantiated decisions to minimise the consequences of man-made and natural disasters and accidents. However, their use in the absence of accepted patterns of system state, making them sensitive to external influences and focused on precise input information, requires new, non-standard approaches, one of which is the interpretation of information used in the system in terms of theory fuzzy sets and the theory of possibilities that form the basis of intelligent information systems.

REFERENCES

1. Yakunina, I.V. (2009). *Methods and devices of environmental control. Environmental monitoring*. Tambov, TSTU: Russia.
2. Diduk, N.N. (2012). The Measures of Internal and External Information (On Example of Probabilistic Situations of Uncertainty). *System Research and Information Technologies*, *4*, 94–110.
3. Zadeh, L.A., Fu, K.S., & Tanaka, K. (2014). Fuzzy sets and their applications to cognitive and decision processes. In: *Proceedings of the US–Japan Seminar on Fuzzy Sets and their Applications, University of California, Berkeley, California*, 1–4 July 1974. Academic Press.
4. Yager, R.R., & Zadeh, L.A. (2012). *An introduction to fuzzy logic applications in intelligent systems.* Springer Science & Business Media.
5. Kofman, A. (1982). *Introduction to the Theory of Fuzzy Sets.* Radio and Communication. Moscow, SU.
6. Shtovba, S.D. (2014*). Introduction to the Theory of Fuzzy Sets and Fuzzy Logic*. Moscow: Russia. Available at http://matlab.exponenta.ru/fuzzylogic/book1/1.php
7. Klir, J. (1990). *Systematology. Automatization of Complex Tasks Decision*. Radio i sviaz: Moscow, US.
8. Beleulmi, S., Bellaouar, A., & Lachi, M. (2014). Cost Optimization of Reliability Testing by a Bayesian Approach. *Mechanics & Industry, 15*, 449–454.
9. Batyrbek, A., Suleimenov, A., Sugurova, L.A., Suleimenov, A.B., & Zhirnova, O.V. (2018). Synthesis of the Equipment Health Management System of the Turbine Units of Thermal Power Stations. *Mechanics & Industry, 19*, 209.
10. Eremeev, I.S., & Dychko, A.O. (2016). Uncertainty Problems in Environmental Monitoring Procedures. *Information Processing Systems*, *6*(143), 45–47.

11. Radionovs, A., & Uzhga-Rebrov, O. (2014). Application of Fuzzy Logic for Risk Assessment/ Izplūdušās loģikas pielietojums risku analīzē. *Information Technology and Management Science*. 17. 10.1515/itms-2014-0007.
12. Yeremeyev, I., & Dychko, A. (2016). Problems of System Analysis of Wastewater Treatment Processes. *Management of Development of Complex Systems, 27*, 170–175.

KONTROLES DATU UZTICAMĪBAS NODROŠINĀŠANA INŽENIERSISTĒMĀS

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K o p s a v i l k u m s

Darbā aprakstīta vadības sistēmas racionalitātes koeficientu, ievadītās nenoteiktības, procesa vadības, sistēmas kļūdu un nenoteiktības līmeņa novērtēšanas pieeja. Balstoties uz identifikācijas teorēmām, ir izstrādāti algoritmi sistēmas stāvokļu identificēšanai. Kontroles datu ticamības palielināšana ar piedāvātajām metodēm nodrošina būtisku informācijas sistēmu darbības uzlabošanu un atvieglo pamatotāku lēmumu pieņemšanu.

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