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POSSIBILITY OF APPLYING HYDROGEN ENERGY IN THE RAILWAY SECTOR

MOGUĆNOST PRIMENE ENERGIJE VODONIKA U ŽELEZNIČKOM SEKTORU

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- hydrogen
- railway
- strategy
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- Southeast Europe (SEE)

Abstract

The application of hydrogen energy in the railway sector should be technologically developed though pilot projects and tests. The International Union of Railways (UIC) implements projects and activities: UIC IR Project H2TR 'Hydrogen technology on railways': training for the application of technical standards; safety requirements (vehicles and infrastructure); authority; train performance; refuelling facilities and hydrogen logistic; business case and financing; operational phase. The global development of technology includes the production of hydrogen and all necessary components, as well as intermodal transport. Hydrogen can be used as: drive energy for sustainable mobility; raw material for industry; medium for producing heat; and electricity for heating; energy storage; costs; price; technological readiness; reliability; security can significantly depend on development in other sectors. Due to the existence of opportunities for the application of a clean and healthy energy, SEE countries are developing various strategies and interstate studies.

Ključne reči
- vodonik
- železnica
- strategija
- tehnologija
- Jugoistočna Evropa (JIE)

Izvod

Primena energije vodonika u železničkom sektoru treba da bude tehnološki razvijena kroz pilot projekte i ispitivanja. Međunarodna železnička unija (UIC) implementira projekte i aktivnosti: UIC IR Projekat H2TR 'Tehnologija vodonika na železnici': obuka za primenu tehničkih standarda; sigurnosni zahtevi (vozila i infrastruktura); ovlašćenja; performanse vozova; postrojenja za dopunu goriva i logistika vodonika; poslovni slučaj i finansiranje; operativna faza. Globalni razvoj tehnologije uključuje proizvodnju vodonika i svih potrebnih komponenata, kao i intermodalni transport. Vodonik se može koristiti kao: pogonska energija za održivu mobilnost; sirovina za industriju; medij za proizvodnju toplote; i struje za grejanje; skladištenje energije; troškove; cenu; tehnološku pripremljenost; pouzdanost; sigurnost može značajno zavisiti od razvoja u drugim sektorima. Zbog postojanja mogućnosti za primenu čiste i zdrave energije, zemlje JIE razvijaju različite strategije i međudržavne studije.

INTRODUCTION

During the last decade, the technology related to hydrogen in the context of energy has been the centre of interest, both in Europe and in the world. There are numerous possibilities for application of hydrogen as a raw material or energy fuel in industry, transport, power generation and the building sector. The main advantage of hydrogen is that its use does not emit CO_2 and does not pollute the environment. Using hydrogen enables the decarbonisation of industrial processes and economic sectors with a reduction in carbon emissions. Analysts estimate that pure hydrogen could meet 24 % of the world's energy demand by 2050, with annual sales of 630 billion Euros. The use of hydrogen as an energy source is a platform for research and innovation, economic growth and new jobs. In 2018, the world's first commercial hydrogen-powered trains began operating in the German region of Lower Saxony, and after several years of testing, 14 hydrogen-powered trains costing 85 million Euros were officially launched in 2022. After the signing of the Paris Agreement in 2016, countries around the world began researching the possibilities of applying a new type of energy that can replace traditional fossil fuels, and most countries favoured hydrogen energy due to its advantages of zero carbon emissions, non-toxicity and high energy density. The Rail Cluster of SEE (RCSEE) makes a significant contribution by informing the railway sector. Since 2019, Great Britain and Germany have launched innovative projects for hydrogen-powered trains. Community of European Railway and Infrastructure Companies (CER) formulates regulation and standardisation in the railway sector, as well as the main elements for the development of Technical Specifications for Interoperability (TSI) or European Standards (EN), as well as EuroSpecs. Specific guidelines will be aligned with International Railway Solutions (IRS) and the needs of rail carriers (both passenger and freight) and infrastructure managers.

HYDROGEN STRATEGY

EU member states have included pure hydrogen in their energy and climate plans, and 26 countries have signed the 'Hydrogen Initiative' and 14 member states have included hydrogen in their national policies for infrastructure for alternative fuels. Some countries have adopted national strategies or are in the process of adopting them. To start the application of hydrogen requires huge financial resources, regulations, new markets, research and innovation on technologies and new solutions related to the market, infrastructure network. Strategic plan for EU countries is shown in Table 1, for UK in Table 2, and for SEE in Table 3.

Table 1. Strategic plan EU countries.

Phase	Description
First phase (2020-2024)	- creating regulatory requirements for a 'well-functioning hydrogen market' - stimulating supply and demand in leading markets - the pursuit of an electrolyser capacity in the EU of at least 6 GW that could produce up to 1 million tonnes (t) of 'clean' hydrogen using renewable energy - decarbonisation of H_2 production - low-carbon hydrogen based on electricity, 'fossil-based' hydrogen
Second phase (2025-2030)	- the pursuit of an electrolyser capacity in the EU of at least 40 GW that could produce up to 10 million tons of 'clean' hydrogen using renewable energy - a network of H_2 gas stations and large-scale warehouses will have to be established - planning a hydrogen network throughout the EU by repurposing parts of the existing gas network
Third phase (2030-2050)	- reaching the maturity of H_2 technology for the production and use of 'clean' hydrogen - a large increase in renewable energy because by 2050, a quarter of renewable energy will be needed to produce hydrogen

Table 2. UK hydrogen strategy.

Phase	Description
First phase early 2020s (2022-2024)	Small scale production Pipeline transport Some transport (buses and railways)
Second phase mid 2020s (2025-2027)	Large production at one location Pipeline and small scale storage Application in the transport industry
Third phase late 2020s (2028-30)	Several large electrolytic projects Development of a large-scale network Wide use in industry, energy and transport
Forth phase mid 2030s onwards	Increasing the volume and range of production Regional or national networks and large-scale storage

Table 3. SEE hydrogen strategies.

Country	Hydrogen strategy
BIH	Bosnia and Herzegovina plans to develop a green hydrogen strategy soon.
Montenegro	The Ministry of Mining, Oil and Gas is currently working on the development of a hydrogen strategy, as it is believed that the use of alternative fuels such as green hydrogen in city traffic could significantly contribute to the reduction of emissions with the greenhouse effect.
Serbia	In the draft of the Hydrogen Strategy, it is stated that Serbia plans to start producing hydrogen from renewable energy sources by 2025, and then to produce around 5,100 tons annually by 2035 and a total of 20,600 tons by 2050. It was also stated that Serbia must understand that the imperative of time is a faster energy transformation with the key participation of science and the profession. /1/
North Macedonia	The tender represents a significant advance in the hydrogen energy sector as it seeks proposals to establish hydrogen fuel infrastructure across the country. The primary objective of the tender is the development of a comprehensive network of hydrogen filling stations and supporting infrastructure to support the use of hydrogen as a clean energy source. Key requirements for proposals include: 1. Hydrogen production plants: setting up hydrogen production units that use renewable energy sources like solar and wind to ensure a low carbon footprint. 2. Refuelling stations: setting up a minimum of 10 hydrogen refuelling stations at strategic locations throughout major cities and highways to facilitate easy access to hydrogen vehicles. 3. Safety measures: implementation of robust safety protocols in accordance with international standards for handling hydrogen, which is known for its high flammability. 4. Technical feasibility: detailed plans showing the technical feasibility of the proposed infrastructure, including storage and distribution systems that can ensure a reliable supply of hydrogen. To ensure the success of the project, proposals must include technologically advanced solutions for hydrogen production, such as electrolysis using renewable energy sources. Charging stations must be equipped with the latest dispensing technology to ensure fast and efficient charging. In addition, proposals must comply with international safety standards for the handling and storage of hydrogen to minimize potential risks.
Albania	The largest deposit of natural hydrogen in the world was discovered in a mine in Albania. Huge amounts of near-pure white hydrogen have been found in a chrome mine. In a recently published study, researchers claim that this H_2 deposit could lay the groundwork for cleaner ways to obtain H_2 that can then be used as a low-carbon or carbon-free fuel source. Researchers that conducted an analysis on the gas as it bubbled through one of the mine's pools show that the purity level of the H_2 was 84 %. The gas also contained much smaller amounts of methane and nitrogen. Based on the current flow of the white hydrogen, the authors of the study find that the pool is currently emitting 11 metric tons of hydrogen per year, which equates to about 75 pounds (34 kilograms) per day, /2/.

HYDROGEN ENERGY

Production methods of H_2: 'electricity-based hydrogen' - produced by electrolysis of water (in an electrolyser, powered by electricity), regardless of the source of electricity.

'Renewable hydrogen' is hydrogen produced by electrolysis of water (in an electrolyser, powered by electricity) and electricity from renewable sources. 'Pure hydrogen' - renewable hydrogen. 'Fossil-based hydrogen' - hydrogen produced using fossil fuels. 'Fossil-based hydrogen with carbon capture' is a subset of fossil hydrogen. 'Low-carbon hydrogen' includes fossil hydrogen with carbon capture and electricity-based hydrogen. 'Synthetic fuels derived from hydrogen' - gaseous and liquid fuels based on hydrogen and carbon, Table 4. The priority is the production of renewable hydrogen based on wind and solar energy. When using hydrogen as a fuel to produce heat or electricity, the product is energy and water.

Table 4. Hydrogen production, /3/.

H_2 production method	Life cycle CO_2 emissions ($kg\ CO_2/kg\ H_2$)	Production costs (Euro/kg H_2)	
		2020	2030
'fossil based' hydrogen			
steam reforming ('grey')	9	1.5	1.5
steam reforming +CC 90 % ('blue')	1	2	2
Methane pyrolysis ('turquoise')	almost zero	pilot phase	2-2.5
'electricity based' H_2			
Electrolysis – current electricity mix	14	6-12	3-6
Electrolysis – renewable electricity ('green')	almost zero	2.5-5.5	1.1-2.4

Hydrogen energy is the chemical energy contained in hydrogen. Procedures for water decomposition: chemical decomposition, direct thermal decomposition, decomposition through thermochemical cycles, electrolytic decomposition.

Storage, transport and distribution of hydrogen

Storage in: vessels under pressure; in liquid state; in the form of compounds that release it easily. Transport and distribution: pipelines; ships; trucks; and trains.

Fuel cell

Hydrogen fuel cell consists of an electrode, a diaphragm and a collector. The main function of the diaphragm is to separate the oxidising agent from the reducing agent. The collector mainly serves to collect the current and to channel the reaction gases. A hydrogen fuel cell is an energy-producing device that directly converts the chemical energy of hydrogen and oxygen into electrical energy. The basic principle is the inverse reaction of water electrolysis, where hydrogen and oxygen are brought to the anode and cathode. Hydrogen diffuses outward through the anode and reacts with the electrolyte, releasing electrons through an external load to the cathode. The catalyst on the anode separates the hydrogen into positively charged hydrogen ions and electrons. Ionised oxygen passes through the electrolyte to the anode compartment, where it combines with hydrogen. One fuel cell produces 0.6-0.8 V. Obtaining higher voltages is achieved by connecting the cells in series. Advantages of using fuel cells: clean and efficient energy; reliable backup power supply; energy storage options; fuel flexibility.

HYDROGEN POWERED TRAIN

The hydrogen train uses a hybrid configuration of hydrogen fuel cells, batteries and electric traction motors. Fuel cells convert hydrogen into electricity, which feeds batteries to provide a stable power source for traction motors. The train's brakes are powered by batteries that store excess energy for later use and further contribute to fuel efficiency. Development of a new generation of hydrogen-powered trains with extremely long life cycles, high power density and improved efficiency is currently underway around the world. Hydrogen-powered trains can reach speeds of up to 140 km/h and travel up to 1,000 km without refuelling, which is ten times more than battery-powered electric trains, while recharging takes less than 20 minutes.

The currently registered disadvantage of hydrogen trains is the amount of energy it can convert into locomotive power, and its energy density is currently lower than that of diesel, which is why it has weaker traction. The efficiency of converting electricity to hydrogen and back is below 30 %, about the same as modern diesel engines, but less than conventional catenary electric traction. Hydrogen is very safe if handled properly, but if not used properly or if the system is accidentally damaged and leaks, there is a risk of fire, so each vehicle has its own discrete fuel system and there are no hydrogen connections between vehicles.

Hydrogen is a high-potential technology with a specific energy per unit mass that is three times higher than traditional jet fuel. Hydrogen rail vehicles are associated with hydrogen charging, hydrogen storage and hydrogen reaction, and because of the risk of hydrogen leaks and explosions that could lead to accidents, strict engineering process requirements and safety measures have been put in place. Initial registered disadvantages of hydrogen trains: high cost of refuelling infrastructure, low efficiency, high energy consumption, high cost of hydrogen itself, limited supply of green hydrogen and requirement for constant replenishment of gas station deposits. Problems with the transport and use of hydrogen and the additional increase in the cost of using hydrogen as an energy source arise because the liquefaction of hydrogen is an energy-intensive process, as well as the fact that it is necessary to maintain a low temperature for long-distance transport and storage, resulting in additional energy losses and associated costs. Currently, the price of hydrogen from renewable sources is about 5 Euros per kg, but the goals defined in the strategies for the period from 2030 to 2050 are for the price to be about 2 Euros per kg, and it includes that the interested party adopts the technology of its own production from renewable energy sources.

RISKS WITH USE OF HYDROGEN ENERGY

Interest in the possibility of using hydrogen-powered trains has increased significantly throughout the world at incredible speed in the last decade. The current situation is reflected in the variety of realisations. Some countries are still in the process of adopting hydrogen strategies, test runs are being run on some railways, while other countries are focused on adopting hydrogen production technologies. During many years of research by scientists around the world, certain risks of hydrogen energy have already been registered, especially that in the case of the application of hydrogen in the railway system, there is a potential risk of leakage and explosion. On the other hand, these stories represent a great challenge for scientists and experts to contribute to the resolution of these difficulties and the adoption of standards and procedures for safe application through their increased engagement.

Ensuring the development and improvement of the safety of the railway system of EU countries derives from the provisions of Directive (EU) 2016/798 of the European Parliament and the Council on railway safety. Common Security Methods (CSM) define security levels, achievement of security objectives and compliance with other security requirements to be met. CSM for assessment and risk assessment is applied in case of technical, operational or organisational changes. Hydrogen propulsion in the railway sector is considered a significant change in the railway system and therefore requires a risk assessment.

The main problems relate to: hydrogen storage; hydrogen leakage; aspects of ventilation; limited knowledge in countries where hydrogen propulsion is not yet used; risk assessment of (i) rolling stock, and (ii) infrastructure; operational concept.

The main goal is how to safely, stably and effectively apply hydrogen energy in the railway transport industry.

Hydrogen storage

Hydrogen is an environmentally neutral element that does not cause any harm and can be stored in liquid or gaseous form and used for energy, fuel or as a raw material for industry. Hydrogen storage is very important as it enables the advancement of technology towards mass use, Fig. 3.

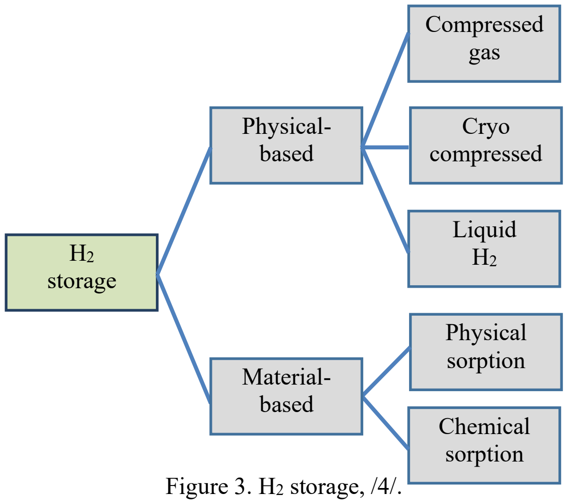

Figure 3. H_2 storage, /4/.

Compared to other fossil fuels, hydrogen on a volumetric basis has a low energy density and increased space requirements, and due to its high gravimetric energy density on a mass basis, it results in minimal weight so that 1 kg of hydrogen gas at room temperature and atmospheric pressure occupies over 11 m^3. The feasibility of storing large quantities in the future will be of great importance, especially from an economic aspect, which means that the density of hydrogen must be increased, and this can be achieved by additional energy input and the use of low temperature storage and high pressure tanks or the use of hydrogen binding materials.

In methods of predicting the consequences for hydrogen storage, several different focus areas have been identified: hazard identification; analysis of consequences; frequency analysis QRA (quantitative risk analysis) is used to assess the risk and calculate the consequences of a hazardous event occurring in and around facilities that typically contain and manage hazardous substances, including hydrogen, Fig. 4. The purpose of the QRA study is to understand the overall risk of the process. Analysis should assist in the assessment or prediction of accidents, fatalities, economic loss, environmental impacts as well as the impact of case scenario assumptions. The outcome of the QRA can also help set the framework for system design requirements and the implementation of preventive measures.

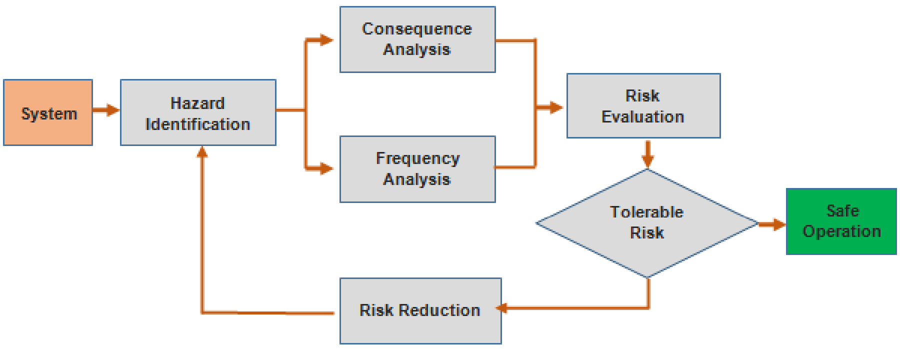

Figure 4. QRA process, /4/.

Hydrogen leakage

Potential leakage risks: dispersion of hydrogen (followed by ignition), hydrogen explosion (followed by a jet flame), instantaneous ignition with resulting jet flame.

From a volumetric point of view, hydrogen leaks about three times faster than natural gas, due to hydrogen containing the smallest molecule, and due to its low gravimetric density, hydrogen has greater buoyancy and will disperse faster into the atmosphere.

Aspects of ventilation

Ventilation system design for hydrogen objects, due to their impact on the risk of fire and explosion, should include several properties of hydrogen, Table 5. Terms and description of key strategies are shown in Table 6.

Although there is broad support for the deployment of hydrogen technology, better public acceptance requires addressing knowledge gaps, safety concerns, and infrastructure challenges through effective public engagement. By fostering a well-informed public and support, hydrogen technology can play a key role in Europe's green energy transition and decarbonisation efforts.

Table 5. Ventilation system design for hydrogen objects.

Hydrogen properties	Description
Low energy density per volume	Hydrogen requires significant pressure for several applications, such as fuel pumps. Operating pressures in these scenarios can be in the region of 700 bar, meaning that even small leaks can create significant flammable clouds.
Wide flammability range	The flammability range of hydrogen (4-75 %) means that a flammable atmosphere is more likely compared to traditional hydrocarbon fuels.
Buoyancy	Hydrogen can rise and accumulate in high areas if there is vertical confinement.
High diffusivity	Hydrogen diffuses quickly, primarily due to its low molecular weight.
Low minimum ignition energy	Without proper ventilation, hydrogen could be dispersed towards potential ignition sources - something that is generally not considered with traditional fuels.
High laminar flame speed	Between concentr. of 25-50 %, the laminar flame speed and subsequent explosion overpressures are greatest.
Detonation	Hydrogen is prone to detonation in the presence of congestion or confinement, leading to higher overpressures and more severe consequences.

Table 6. Key strategies terms and description.

Terms	Description
Providing clear and accessible information	Providing clear and accessible information about hydrogen technology, its benefits and safety is essential. Education campaigns should be aimed at addressing region-specific issues and knowledge gaps in order to better understand and address misconceptions/concerns.
Transparent communication	Transparent communication in order to build trust with the involvement of state institutions and the scientific community. The public should be informed about the environmental benefits of hydrogen technology.
Public reluctance	Public reluctance regarding hydrogen infrastructure, especially in residential areas, must be addressed through inclusive planning processes and community engagement.
Gender and age inclusion	Gender and age inclusion is achieved by making efforts to increase the inclusion of women and younger people (schoolchildren and students) in discussions about hydrogen technology, which allows consideration of different perspectives.

Operational concept

Hydrogen fuel cell trains can run on hydrogen, and the end product is just water and heat. These trains are a good alternative to diesel engine locomotives where the railway tracks do not have a contact network, and there is the possibility of dual operation at the same time with electric and hydrogen propulsion. It is important to note that when using hydrogen energy, railway companies that have preserved suitable old locomotives can repair them and convert them into hydrogen-powered locomotives.

Vanguard is a fast-growing spin-out of one of the UK's leading universities which bases its work on decades of research into the mobility and energy sectors in order to deliver the holistic solutions necessary to provide decarbonised transport systems. Vanguard addresses the rail market and drives the decarbonisation of heavy transport through the development of hydrogen and battery solutions consisting of a propulsion system and long-term hydrogen supply and charging infrastructure.

The essence of the operational concept of hydrogen-powered trains lies in the technology, the state of the art and the development of the projects.

Designing and introducing new hydrogen trains involves several (complementary or alternative) technologies: fuel cells with batteries (as fuel cell only options are not currently available); ICE (internal combustion engines); pressurised hydrogen storage and shipboard storage (gas vs. liquid); battery; ammonia (and other alternative options).

EU train manufacturers working on delivering hydrogen-powered trains: Alstom Coradia (ILint and stream); Siemens Mireo +H; Staedler Flirt H_2; PESA Bydgoszcz (shunting locomotive SM42 6Dn).

HydroSHUNTER (Figs. 5 and 6) is a Class 08 locomotive which runs on hydrogen instead of diesel, with technical specifications listed in Table 7. This is made possible through Vanguard's own hydrogen-hybrid retrofit powertrain.

Figure 5. HydroSHUNTER /5/.

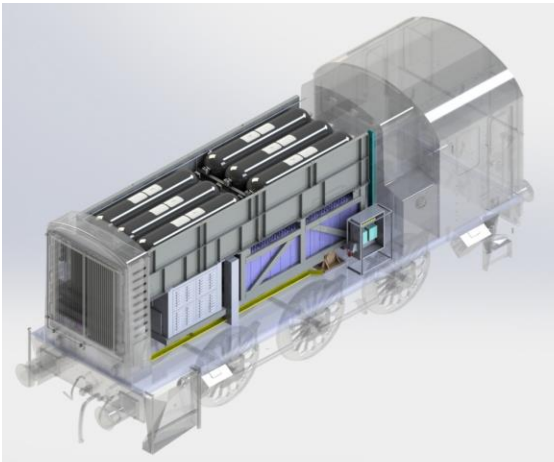

Figure 6. HydroSHUNTER /5/.

HydroSHUNTER offers the following operational benefits:

- No impact on existing driver/operator controls so no driver retraining is required post conversion.
- A proven, reliable platform for the hydrogen power train offering greater efficiency with zero carbon emissions without scrapping useable rolling stock.

- Zero carbon and zero particulate emissions mean Hydro-SHUNTER is ideal for use in environments such as urban or residential areas where air quality is a concern.

Table 7. HydroSHUNTER Technical specification, /5/.

Mass	50 t
Track gauge	1,435 mm
Tractive effort	155 kN
Traction power	260 kW
Power sources	40 kW fuel cell 200 kWh lead acid battery
Hydrogen fuel capacity	60 kg
Braking	air & vacuum*
Maximum speed	15 mph**
Operating endurance	at least 20 h

*regenerative braking also available
**25 mph possible via regearing

Hydrogen transport by rail

As the infrastructure of special pipelines for the transport of hydrogen has not yet been built, this technological gap can be overcome by transporting hydrogen by freight trains by cargo companies. Hydrogen transport can continue with cargo ships. Hydrogen remains bound in liquid so that standard tank cars can be used for rail transportation.

ERCI AND RCSEE

European Railway Clusters Initiative (ERCI) is leading meta-cluster of the railway industry in Europe uniting 17 innovation clusters from 16 European countries (Austria, Belgium, Bosnia & Herzegovina, Croatia, France, Germany, Italy, Montenegro, North Macedonia, Poland, Serbia, Slovenia, Spain, Sweden, Turkey, United Kingdom). Once or twice a month, ERCI organises webinars where companies and scientific institutions present their innovative solutions for the European railway system of the future. Usually, two speakers from different countries highlight webinar topic from their perspective. LEADER 2030 is ERCI Project. ERCI member projects are: E-BOOST; IDEALIST, S-ACCESS, STARS, E-CORRIDOR. Principles and activities of ESCEE are presented in Table 8.

Table 8. Principles and activities RCSEE.

Terms	Description
Strategic goals	- modernisation of railway system in the region; - harmonization of standards of railway systems in Southeast Europe; - increase of productivity and competitiveness in the international market; - improved external reputation and better positioning with EU and Brussels; - PR activities in the EU for improved financial support to national railways in the region; - initiate implementation of innovative technologies in the region, and increased transparency in this process; - synchronisation of laws and regulation in the region with the EU, enabling intensified passenger and cargo transfer in this part of Europe development of public-private partnership in the railway sector in the region;
Activities	- creation of quality databases; - international cooperation; - large annual regional Conference of the cluster (held every year in another state); - organisation of other events (regional member meetings, roundtables work, with regional media and the public); - coordination of national railways for active participation in joint activities and fulfilment of strategic goals of the cluster); - cooperation and intensified communication with municipal governments in the region;
Cluster sectors	- education and certification - logistics, infrastructure and IT - international cooperation and strategic planning

CONCLUSIONS

The paper deals with the research of possibilities for improving the railway system when introducing hydrogen energy and is focused on the needs of railway companies (infrastructure, passenger transport, freight transport and maintenance of railway vehicles) with a special focus on supporting managers in making important decisions related to hydrogen energy, as and other interested experts.

The possibility of introducing hydrogen-powered trains can be a turning point, similar to when steam traction was replaced by diesel propulsion, and diesel propulsion by electric power. It can be considered that hydrogen-powered trains represent a revolutionary change at the world level, like a wave that started almost all countries in the world to devise strategies on how to adopt the new technology in the most efficient way.

The current level of development of the society as a whole offers the possibility to involve the wider public, i.e., everyone has the right to influence from the highest state top, through scientists, managers, experts, students, researchers, as well as every individual, and such contributions in decision-making are really valuable for society as a whole.

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