Alan Beroud
Mgr inż.
Szybka Kolej Miejska sp. z o.o.

DOI: 10.35117/A_ENG_23_01_01

Practical use of hydrogen as a strategic energy carrier on the example of the railway sector

Abstract: In the article, the author submits and analyzes the assumptions of the EU climate and energy policy. He also indicates and describes the condition and prospects of the Polish energy sector in the context of the use of new energy sources. The publication includes - supported by calculations - arguments for the use of hydrogen as a strategic energy source on the example of the railway sector.

Keywords: Hydrogen; Energy; Railway, EU

Introduction

The energy crisis triggered by actions taken by the Russian Federation against EU member states supporting Ukraine has highlighted to policymakers the necessity of accelerating the transition from fossil fuels to artificially produced alternatives. It is crucial, however, to adhere to environmental protection principles throughout this process. Combining these objectives presents challenges, though it is no longer as daunting as it was perceived two or three decades ago. Currently, hydrogen is seen as the most promising fuel of the future. Unlike wind and solar energy, hydrogen is not dependent on natural forces, thus ensuring stable and secure energy supplies for both the industrial sector and the broadly defined services sector.

The railway sector can be viewed both as part of the industrial sector—encompassing the manufacturing, modernization, maintenance, and repair of railway vehicles—and as a service sector that enables efficient transportation on local, national, and international levels. Hydrogen can play a pivotal role as a fuel not only for the future but for the present, especially in urban rail systems that serve large metropolitan areas. Alongside subways, these systems are integral to the functionality and efficiency of urban and suburban transportation networks. In Poland, two metropolitan areas already rely on or are poised to benefit significantly from urban rail systems. The first is the Warsaw metropolitan area, and the second is the Silesian metropolitan area. Both systems serve or have the potential to serve hundreds of thousands of passengers daily. Additionally, efforts to develop urban rail systems are underway in the rapidly growing Kraków metropolitan area, which has recently surpassed one million residents. Consequently, energy costs and supply stability are critical issues for the railway sector.

EU Climate and Energy Policy Objectives

Amid the intensifying energy crisis and environmental pollution issues resulting from the greenhouse effect, EU member states have undertaken significant efforts toward decarbonization and the transition to renewable energy sources (RES). It must be noted, however, that this process is both costly and time-intensive. Consequently, coal mining—both hard and lignite—continues in some EU countries. While some states are phasing out these resources, others face significant challenges in doing so due to their economies' heavy reliance on coal, which remains a vital energy source. Poland is among these nations.

Nevertheless, EU membership provides access to financial resources that can significantly support the transition to alternative energy sources.

Currently, EU member states, including Poland, have committed to numerous goals and obligations stemming from the Paris COP summit. These commitments are aligned with the EU's overarching energy and climate policies and include:

- A 95% reduction in greenhouse gas emissions,
- Achieving net-zero CO2 emissions, and
- Complete decarbonization of the power sector.

The message of the Paris COP summit is reinforced by a variety of legal frameworks adopted by member states in the area of research under review. A particularly important regulation in this context is AFID—the Alternative Fuels Infrastructure Directive (Directive 2014/94/EU), adopted by the European Parliament on October 22, 2014. This directive aims to integrate alternative fuel infrastructure into the EU economy. However, it is worth noting that AFID does not impose significant obligations related to the use of hydrogen. The directive would greatly benefit from requiring the implementation of hydrogen refueling infrastructure.

Another key document is RED II—the Renewable Energy Directive (Directive 2018/2001/EU) adopted on December 11, 2018. According to this directive, to facilitate the faster, more stable, and efficient adoption of renewable energy sources, each member state must ensure that fuel suppliers achieve a 14% share of renewable energy in final energy consumption in the transport sector. The directive anticipates that this issue will be fully addressed by 2030. Guarantees of origin for fuels, directly tied to environmental protection efforts, are an essential component of this directive.

To calculate the so-called "minimum share," member states must include renewable liquid and gaseous transport fuels of non-biological origin. This requirement applies when these fuels are produced as key components in conventional fuel production. In the author's view, guarantees of origin should also encompass renewable gas sources.

The guarantee system in this domain should extend to non-renewable energy sources. Guarantees of origin, currently applied to renewable electricity, should be expanded to include renewable gas. Such a comprehensive energy policy would enable the introduction of guarantees for hydrogen.

1. Strategic goals of the EU climate and energy policy [1]

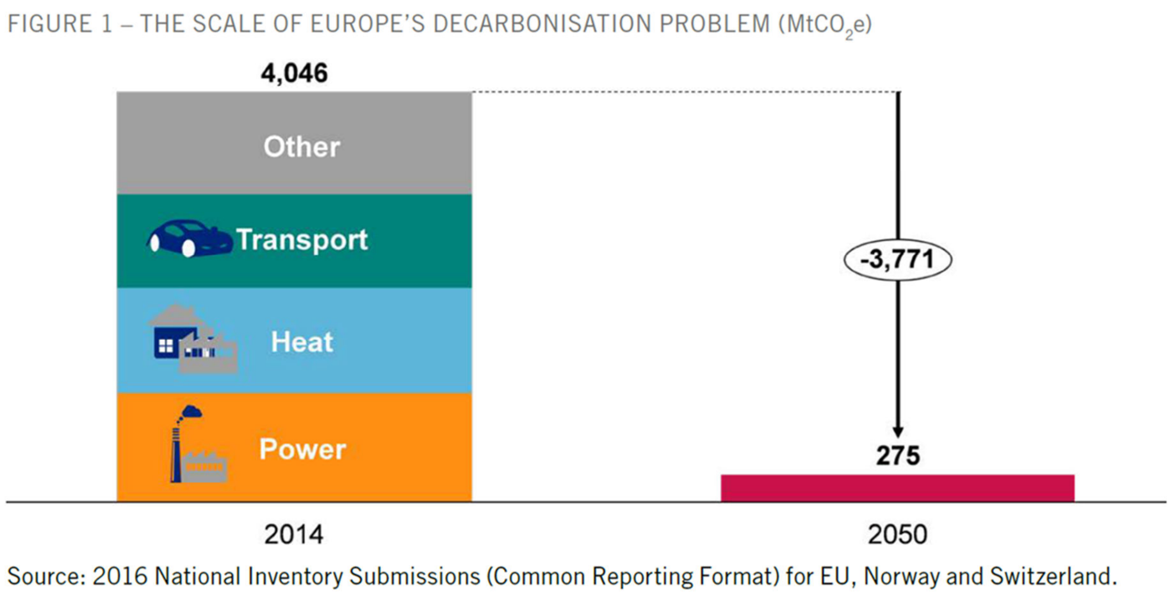
Development of Poland's Energy Sector Through the Use of New Energy Sources: Current State and Prospects

The primary challenge facing the development of Poland's energy system is the delay in implementing necessary changes. For many years, it has been evident that Poland's capacity to produce hard coal and lignite is diminishing. Additionally, as awareness of climate issues has grown within the EU, the process of decarbonization and the transition to renewable energy sources (RES) has accelerated.

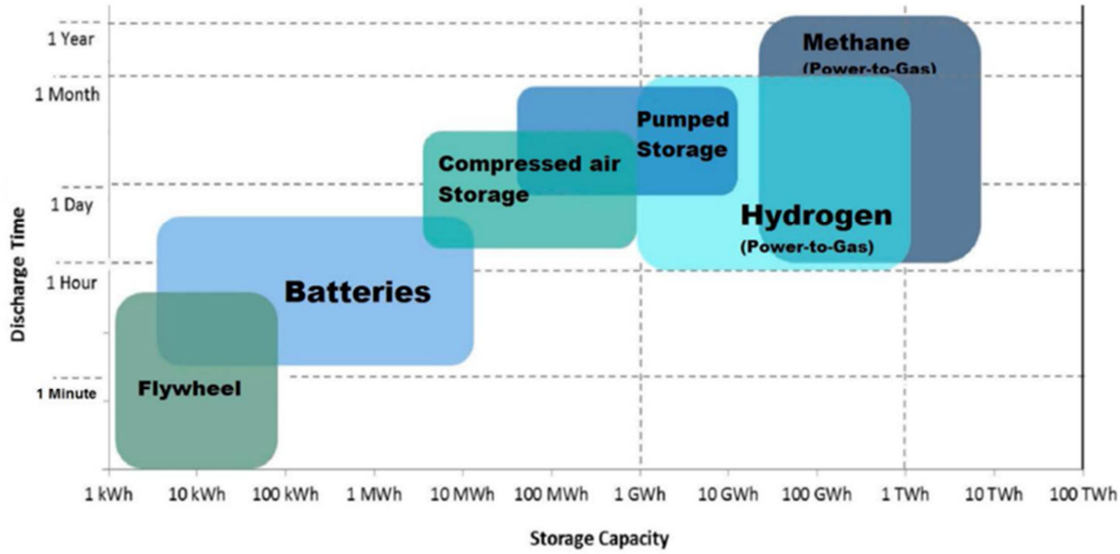
The only government that proposed a coherent plan in this regard was that of Prime Minister Jerzy Buzek. This plan should have been consistently pursued by successive administrations, regardless of their political orientations. Unfortunately, we now face accumulated challenges stemming from years of inaction. Addressing these challenges will become increasingly difficult without substantial external assistance, primarily from the EU.
Within the next two decades, Poland is obligated to phase out 20 GW of energy currently generated from hard coal and lignite. An unresolved question remains whether we can complete the construction of nuclear power plants in time, as nuclear-related projects are still in their preliminary phases, far from even feasibility studies.

In the author's opinion, Poland's energy balance should include at least one energy source with a capacity comparable to the Kashiwazaki-Kariwa nuclear power plant in South Korea. The capacity of this Korean plant is 7,965 MW, achieved through seven reactors that utilize modern, environmentally friendly technologies to ensure safety. Additionally, 10 GW of capacity should come from gas-based sources, supported by adequate storage facilities that are essential for ensuring the stability of the national energy system. Expanding storage capacity is also logical in light of Poland's growing ability to liquefy LNG at the Świnoujście terminal and the potential further development of LNG infrastructure in the country.

The remainder of Poland's energy capacity should be gradually replaced with renewable energy sources. This approach aligns with the development trajectory of the European energy sector. However, the critical issue to address in this context is energy storage. Currently, the only viable technology capable of storing energy on the scale necessary to meet strategic decarbonization goals (measured in terawatt-hours) is hydrogen-based technology.



2. The decarbonization process on the example of the EU, Norway, Switzerland [3]



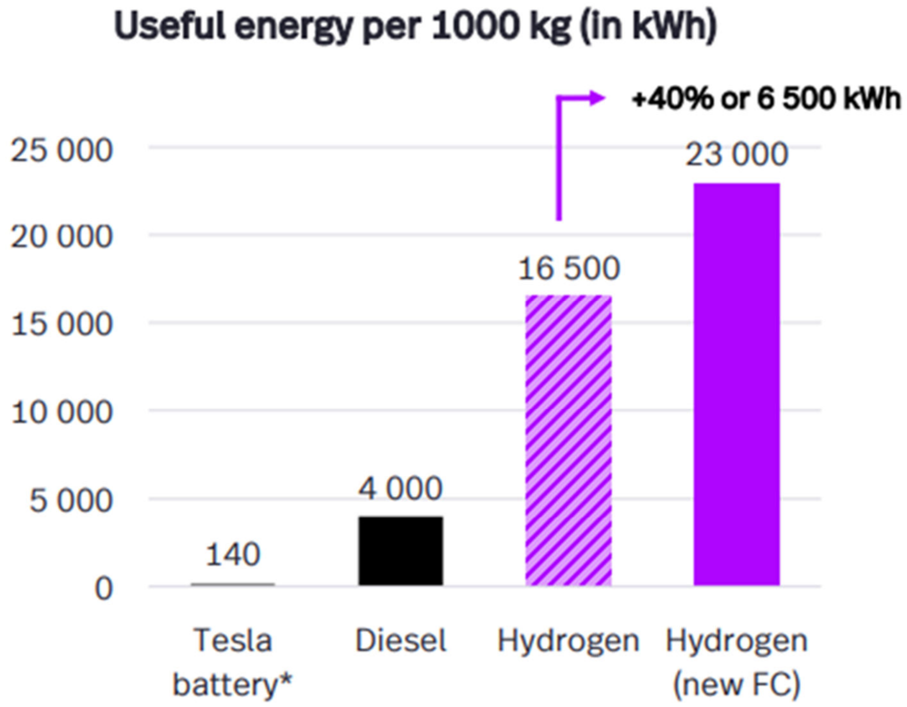
3. Features of hydrogen as a universal fuel of the 21st century [4]

Hydrogen as the Future of Energy - Key Conclusions

Based on the analysis of the illustrations above and the available source materials, several critical conclusions can be drawn that, in the author's opinion, unequivocally support the utilization of hydrogen:

1. **Energy Storage Feasibility**: To store just 10% of the annual electricity consumption in Poland (both individual and institutional consumers) using currently available battery technologies, an estimated total battery weight of 160 billion tons would be required. This figure highlights the impracticality of resisting technological progress to maintain the status quo. Hydrogen presents a far more feasible and efficient alternative for large-scale energy storage.
2. **High Energy Density**: Hydrogen's high energy density makes it exceptionally versatile, allowing for effective application across virtually all modes of transport. Moreover, the longer the distance and the greater the power demand, the more efficient hydrogen becomes as an energy source, making it particularly suitable for industries with high energy requirements, such as aviation, shipping, and long-haul road transport.
3. **Enhanced Storage Capacity**: Utilizing hydrogen in gas compression systems significantly increases storage capabilities, enabling capacities of up to 4.5 TWh. This is a critical advantage in the transition to renewable energy sources, as it addresses the need for large-scale energy storage to balance fluctuations in supply and demand.
4. **Advancements in Fuel Cell Technology**: Continuous progress in improving the efficiency and stability of fuel cell systems further strengthens the case for hydrogen. These advancements enhance the reliability and scalability of hydrogen-based energy solutions, making them increasingly viable for widespread adoption.

In conclusion, these factors collectively present a promising outlook for a future with significantly reduced reliance on fossil fuels, driven by hydrogen's potential to revolutionize energy storage, transportation, and overall energy systems.



4. Conversion efficiency [6]

In summary, with regard to environmental protection, it is crucial to emphasize that the combustion of fossil fuels remains the primary source of pollutant emissions. On a global scale, over 75% of NOx and SO2 emissions, 70% of CO emissions, more than 75% of particulate emissions, and over 90% of CO2 emissions are generated by the combustion of hard coal, lignite, petroleum, and natural gas.

The **Clean Air for Europe (CAFE)** initiative, under its Thematic Strategy on Air Pollution, outlines a significant reduction in chemical emissions over an eight-year period, targeting completion by 2022. This ambitious strategy underscores the urgent need for transitioning to cleaner energy sources, highlighting the importance of mitigating the environmental impact of fossil fuel combustion.

Tab. 1. Reduction of emissions of selected chemical compounds (CAFE)

SO2	82%
NOx	60%
PM 2,5	59%

Own study

Hydrogen-Powered Train vs. Electric Train: Analytical Comparison

Given the data presented above and supported by available forecasts, hydrogen holds the potential to become a strategic energy carrier in the rail sector. A direct hydrogen-powered train eliminates energy transmission losses and offers higher process efficiency due to the absence of central fuel generation. Furthermore, hydrogen negates the need for investments in central and traction energy transmission infrastructure.

When comparing an electric train to a hydrogen-powered locomotive, it is essential to consider the specifics of the Polish energy system, which is predominantly coal-based. Below is an analytical comparison, including efficiency calculations.

Formulas and Calculations

- **η el netto** – net electric energy efficiency
- **E ch pal** – chemical energy of the fuel
- **E eln** – net electric energy
- **p** – amount of fuel consumed
- **E el used** – energy consumed by the train
- **W d** – calorific value of the fuel
- **η łn** – energy transmission efficiency

Efficiency Formula

ηelnetto=EelnEchpal=Eelzuz˙ytaηłnp×Wd=41%η el netto = \frac{E eln}{E ch pal} = \frac{\frac{E el zużyta}{η łn}}{p × W d} = 41\%ηelnetto=EchpalEeln=p×WdηłnEelzuz˙yta =41%

Efficiency Components:

ηelnetto=ηk×ηtp×ηm×ηg×(1−Σ)×ηecrη el netto = η k × η tp × η m × η g × (1 - Σ) × η ecrηelnetto=ηk×ηtp×ηm×ηg×(1−Σ)×ηecr

Where:

- **η k** – boiler efficiency
- **η tp** – internal efficiency of the steam turbine
- **η m** – mechanical efficiency of the steam turbine
- **η g** – generator efficiency
- **Σ** – internal energy consumption of the source
- **η ecr** – energy cycle efficiency

Calorific Value and Emissions

- **Calorific value of coal (W d):** 21.77 MJ/kg
- **Emission factor (eCO2):** 93.49 kg/GJ

Electric Train Example: Impuls 45WE (SKM Warsaw)

Assumptions:

- Energy consumption: 760 kWh/100 km

Eelzuz˙yta=760 kWh=2736 MJ=2.736 GJE el zużyta = 760 \text{ kWh} = 2736 \text{ MJ} = 2.736 \text{ GJ}Eelzuz˙yta=760 kWh=2736 MJ=2.736 GJ
1 kWh = 3.6 MJ3.6 \text{ MJ}3.6 MJ

- Net electric energy:

Eeln=Eelzuz˙ytaηtp=2736 MJ0.95=2880 MJE eln = \frac{E el zużyta}{η tp} = \frac{2736 \text{ MJ}}{0.95} = 2880 \text{ MJ}Eeln=ηtpEelzuz˙yta=0.952736 MJ=2880 MJ

- Chemical energy of the fuel:

Echpal=Eelnηelnetto=2880 MJ0.41=7.024 MJE ch pal = \frac{E eln}{η el netto} = \frac{2880 \text{ MJ}}{0.41} = 7.024 \text{ MJ}Echpal=ηelnettoEeln=0.412880 MJ =7.024 MJ

- Coal consumption:

p=EchpalWd=7024 MJ21.77 MJ/kg=322 kg of coal per 100 kmp = \frac{E ch pal}{W d} = \frac{7024 \text{ MJ}}{21.77 \text{ MJ/kg}} = 322 \text{ kg of coal per 100 km}p=WdEchpal=21.77 MJ/kg7024 MJ=322 kg of coal per 100 km

- CO2 emissions:

ECO2=eCO2×Echpal=7.024 GJ×93.49 kg/GJ=656.67 kg CO2E CO2 = eCO2 × E ch pal = 7.024 \text{ GJ} × 93.49 \text{ kg/GJ} = 656.67 \text{ kg CO2}ECO2=eCO2×Echpal=7.024 GJ×93.49 kg/GJ=656.67 kg CO2

- Cost of fuel (coal price in 2021: 996.60 PLN/ton or 0.997 PLN/kg):

Fuel cost per 100 km=322 kg×0.997 PLN=321 PLN\text{Fuel cost per 100 km} = 322 \text{ kg} × 0.997 \text{ PLN} = 321 \text{ PLN}Fuel cost per 100 km=322 kg×0.997 PLN=321 PLN

Hydrogen Train Example: Coradia iLint (Alstom)

Assumptions:

- Range: 800 km on two hydrogen tanks (90 kg each)

Hydrogen consumption per 100 km=180 kg800 km×100=22.5 kg\text{Hydrogen consumption per 100 km} = \frac{180 \text{ kg}}{800 \text{ km}} × 100 = 22.5 \text{ kg}Hydrogen consumption per 100 km=800 km180 kg×100=22.5 kg

- Hydrogen price forecast for 2030: 1.8 EUR/kg

Fuel cost per 100 km=22.5 kg×1.8 EUR=40.5 EUR\text{Fuel cost per 100 km} = 22.5 \text{ kg} × 1.8 \text{ EUR} = 40.5 \text{ EUR}Fuel cost per 100 km=22.5 kg×1.8 EUR=40.5 EUR
Using an exchange rate of 4.65 PLN/EUR:
Fuel cost per 100 km=40.5×4.65=188.33 PLN\text{Fuel cost per 100 km} = 40.5 × 4.65 = 188.33 \text{ PLN}Fuel cost per 100 km=40.5×4.65=188.33 PLN

Summary

Considering a ten-year investment horizon in rail vehicles, and factoring in the proposed hydrogen price, the coal price from 2021 (notably lower than current levels), and the specifics of the Polish energy sector, hydrogen-powered trains appear highly competitive.

- **Cost Comparison:**
  - Electric train operating costs: 321 PLN/100 km
  - Hydrogen train operating costs: 188.33 PLN/100 km

Hydrogen-powered trains present significantly lower operational costs.

- **Infrastructure and Emissions:**
  - Electric trains require substantial energy infrastructure investments.
  - CO2 emissions:
    - Electric train: **656.67 kg/100 km**
    - Hydrogen train: **0 kg/100 km**

The adoption of hydrogen minimizes energy infrastructure costs and eliminates CO2 emissions.

- **Capital Costs:**
  - Electric train cost: ~30 million PLN (electric multiple unit)
  - Hydrogen train cost: ~45 million PLN (Alstom data)

Hydrogen-powered trains demonstrate long-term cost-effectiveness, reduced environmental impact, and infrastructure advantages, warranting thorough evaluation for future rail investments.

Source materials

[1] Prezentacja „Hydrogen as an alternative fuel", 2nd Polish Conference on Hydrogen and Technology, Nexus Consultants; Gdynia 2018, slajd 2

[2] PMG Swarzów (w wyeksploatowanym złożu gazu wysokometanowego) o pojemności 90 mln m³; PMG Strachocina (w wyeksploatowanym złożu gazu wysokometanowego) o pojemności 360 mln m³; PMG Brzeźnica (w wyeksploatowanym złożu gazu wysokometanowego) o pojemności 65 mln m³; PMG Husów (w wyeksploatowanym złożu gazu wysokometanowego) o pojemności 500 mln m³; PMG Wierzchowice (w wyeksploatowanym złożu gazu zaazotowanego) o pojemności ponad 1 200 mln m³; PMG Mogilno (w kawernach solnych) o pojemności 411,89 mln m³ (pierwsze 2 komory oddane do eksploatacji w 1997 roku); PMG Kosakowo (w kawernach solnych) o pojemności 145,5 mln m³ (w 5 kawernach, ostatnia oddana do eksploatacji w 2016)

[3] Prezentacja "Hydrogen as an alternative fuel"…., slajd 6

[4] Tamże, slajd 8

[5] Za twórcę systemu działania ogniw wodorowych uważa się Christiana Friedricha Schönbeina. Ze swoim naukowym wynalazkiem podzielił się on z czytelnikami w styczniu 1839 roku na łamach „Philosophical Magazine" („Magazynu Filozoficznego"), z których większość stanowili przedstawiciele świata nauki. Na podstawie prac studyjnych tego niemiecko – szwajcarskiego chemika Walijczyk William Grove stworzył pierwsze działające ogniwo paliwowe. Prace nad ogniwami paliwowymi kontynuowano również w latach następnych. I tak w 1887 roku Walther Hermann Nernst sporządził opis matematyczny działania ogniwa paliwowego (równanie Nersta). W 1958 roku amerykańscy oraz brytyjscy naukowcy wyprodukowali w oparciu o posiadaną wówczas w tej dziedzinie wiedzę ogniwa paliwowe służące spalaniu wodoru. Jak to często bywa z odkryciami naukowymi (wynalazkami) ogniwa te nie znalazły jednak praktycznego zastosowania. Wpływ na

to ma bez wątpienia lobby paliwowe skupione wokół producentów paliw kopalnych, którzy niechętni byli wszelkiego rodzaju innowacjom zagrażającym ich interesom ekonomicznym. W latach 60. ubiegłego stulecia w USA zaczęto wykorzystywać ogniwa z membranami polimerowymi lub AFC jako źródło elektryczności oraz wody. Znalazły one swoje zastosowanie w projektach kosmicznych (Gemini 5, Apollo). Problemem pozostawały koszty wykorzystywanych w produkcji ogniw paliwowych materiałów. Dalszy postęp technologiczny, który przypadł na dwie ostatnie dekady XX wieku przyczynił się do rozwiązania większości z omówionych wyżej wyzwań (między innymi wykorzystano membranę polimerową jako elektrolit, zmniejszono ilość palatyny używanej do produkcji ogniw). Tym samym przyniosło to za sobą możliwości zastosowania ogniw paliwowych do celów komercyjnych.

[6] Prezentacja "Hydrogen as an alternative fuel"

[7] Podana emisja CO2 oraz Wd węgla za stroną internetową www.kobize.pl

[8] Strona internetowa https://globenergia.pl/koszt-produkcji-wodoru-z-wykorzystaniem-pv-spadnie-do-07-18-euro-kg-w-2030-roku/