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Development of low-emission hydrogen energy in Egypt's energy industry

Abstract: The article focuses on the analysis of one of the key area of the energy system, which is energy from renewable sources. The authors focused on considerations covering the Egyptian energy sector. Possibilities and limitations of the Egyptian energy sector in the renewable energy segment were presented. The attention has been put on the benefits that may occur from the cooperation agreements signed by Egypt in field of hydrogen based energy. The advantages of the solutions taken in opposition to the costs of hydrogen energy were presented as a significant but acceptable disadvantage in terms of the need to take measures to increase the share of renewable energy sources in Egypt. Cost analysis was performed on examples, based on market forecasts. The article takes into account the stability defined as the two decades long stabilization of the Egyptian energy sector, which translates into the implementation of the adopted plans and assumptions by this country.

Keywords: Hydrogen energy; Egypt, Renewable energy sources; Low-emission energy

Introduction

In recent years, a noticeable increase in interest in hydrogen energy has emerged among scientific centers representing both the public and private sectors. This also implies the interest of countries that are importers of raw materials in economic terms, as a potentially profitable branch of energy and a possible alternative to other energy sources, in the context of the general trend of minimizing emissions associated with the energy sector. Due to the positive feedback from experts regarding technical and economic possibilities, hydrogen energy represents a hope for many economies, being the best substitute form for conventional, non-renewable energy sources. The above applies to countries within the European Union, as well as a number of other highly developed countries and states aspiring to play an increasingly significant role on the “geopolitical chessboard,” an example of which is Egypt.

Since 2019, Egypt has met its energy needs solely based on domestic production [9]. In 2022, 90.5% of energy generated in Egypt came from natural gas and crude oil, 7.3% from hydropower plants, and 2.2% from renewable sources [9]. The low share of renewable sources in Egypt’s energy structure does not mean a lack of potential for this country to restructure its own energy sector to reduce emissions and establish a kind of energy security as a preventive measure for the future. The Egyptian authorities have committed to increasing the share of energy from RES to 42% by 2035 [9].

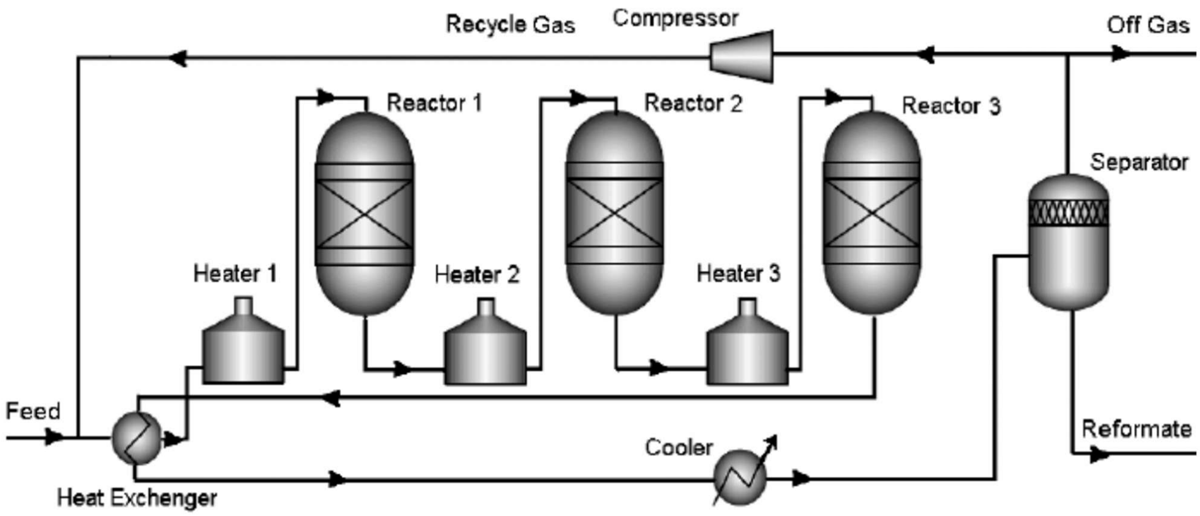
In recent years, there has been growing interest among decision-makers responsible for the functioning of Egypt’s energy sector in green hydrogen. Energy produced from hydrogen is one of the cleanest forms of energy, while also being inexhaustible, similar to energy from renewable sources or nuclear power [4]. The subject of this work is therefore to review aspects of hydrogen energy in a broader context, measured by the possibilities as well as the limitations of Egypt’s energy sector, taking into account infrastructure issues, economic benefits, necessary technical improvements regarding storage and transport, and—most importantly—research issues aimed at adapting the energy system to modern technologies. One of the fastest-growing industrial sectors is freight and passenger transport, including rail transport. The latter is increasingly using new technologies, also in the area of energy acquisition as a source for powering train sets. Among them, hydrogen is playing an increasingly important role, which, according to the assumptions of the Egyptian authorities, should become a primary energy source in the future. Considering the benefits of hydrogen energy, it is possible to put forward a research hypothesis stating that hydrogen energy may be an opportunity for Egypt's economic development, and its advantages outweigh the disadvantages in the form of necessary technical restructuring. According to the authors of this publication, an in-depth analysis of the topic, supported by foreign studies often of a primary source nature, will allow for confirmation or refutation of the presented hypothesis and for establishing a thesis that constitutes a substantive culmination of the information presented.

This publication was created as a result of scientific research that included a literature query in the relevant field. Among the research methods used, the case study and scenario methods deserve special attention. These were preceded by the typical method for political science and administration—analysis of existing sources, which forms the basis for applying the above-mentioned research methods. The case study method allowed for the selection of key issues addressed in the scientific article and subjecting them to detailed analysis using interdisciplinary tools to ultimately formulate conclusions. The latter primarily concern the future, which enabled the authors of the article to smoothly transition to the scenario method.

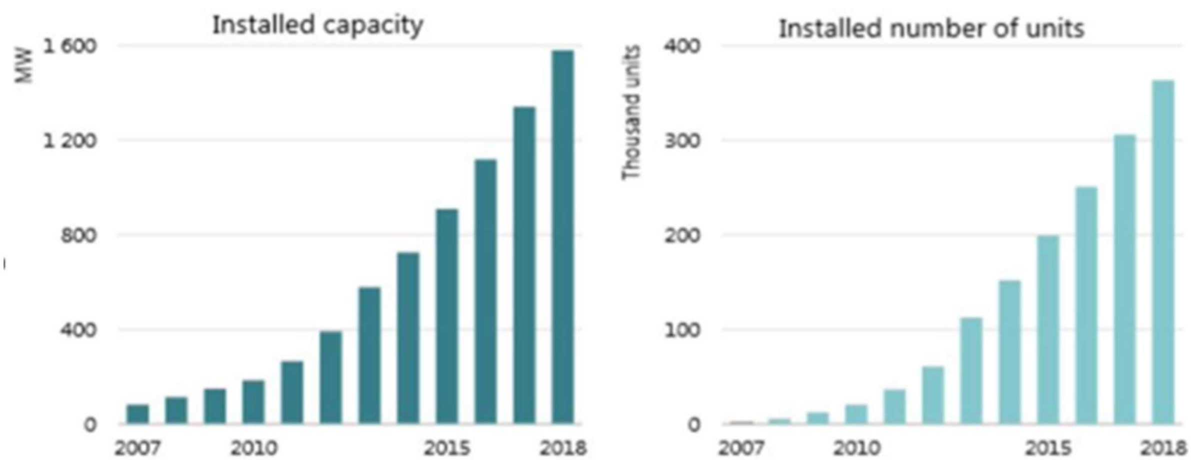
General characteristics of energy obtained from hydrogen, taking into account the price competitiveness of this raw material

Global energy and climate policy forces the search for alternative solutions in the energy sector to obtain competitive and environmentally friendly electricity (Sikora, 2018). The use of hydrogen-rich gases from petrochemical plants and steel mills is therefore common. Modern gas turbines can also run on a mixture of gases containing hydrogen, an example being a 40 MW unit in a refinery in Daesan, South Korea, which uses gases with a hydrogen content of up to 95%. Its lifespan under the given parameters is estimated at a minimum of 20 years. The absence of CO2 emissions during the process of converting hydrogen into electricity and heat is also an advantage of energy conversion based on fuel cells. The only by-product of this process is water, which does not pose a potential threat to the environment. These cells have the potential to achieve an energy efficiency level of over 60%, while maintaining higher efficiency at loads that do not constitute a full load. This is beneficial in the context of conducting flexible operations, such as load balancing [13].

A disadvantage of obtaining clean energy from the transformation of compounds containing hydrogen is the cost of obtaining the hydrogen itself, which in essence exceeds the level of energy gains resulting from the combustion of hydrogen, in turn supporting the argument of the unprofitability of this process. One of the most important advantages of hydrogen-derived energy is its zero emissions. The main product resulting from this process is water in a gaseous form (water vapor), which, unlike carbon dioxide and sulfur dioxide—products of burning conventional fuels whose main components are short-chain hydrocarbons created by the cracking of longer-chain hydrocarbons and the subsequent reforming process—does not pose an environmental hazard. These processes increase the degree of branching of the mentioned compounds, which implies easier combustion compared to straight-chain isomers. In this context, it is worth noting that hydrogen as a gas has a relatively low ignition temperature and a surprisingly high calorific value, which is an argument in favor of using hydrogen as an energy source. Unlike hydrocarbons, there is no need to carry out cracking and reforming processes. The energy gains are also exceptionally high relative to the molar mass of this element. Priority seems to be given to aspects of storing and transmitting hydrogen on an industrial scale, as well as optimizing the production process (Sikora, 2018).

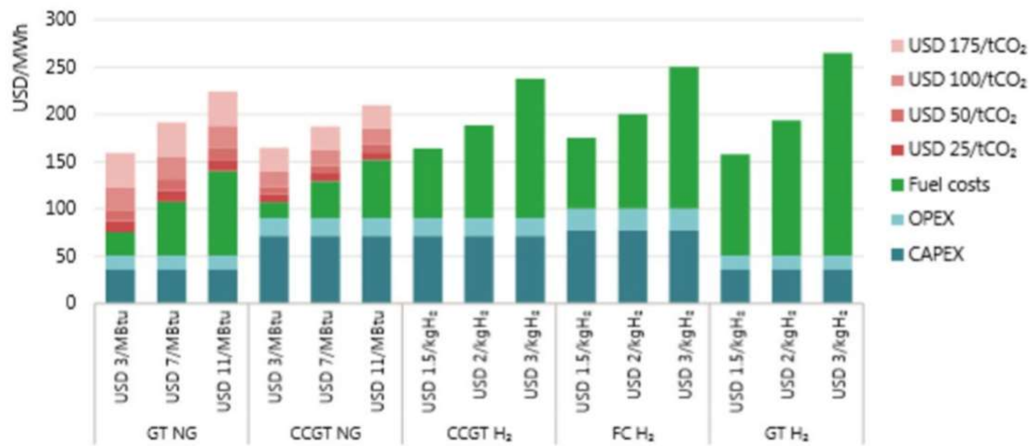


1. The course of the catalytic reforming process of naphtha [23]



2. Development of stationary fuel cell capacity over the years 2007-2018 [24]

Presented in the chart above, the significant increase in the share of stationary fuel cells in overall energy production shows that it is justified to consider this resource as an alternative in light of the necessity to continually reduce emissions resulting from the combustion of conventional energy resources, with coal and natural gas still at the forefront. Hydrogen is a clean and flexible energy carrier derived from basic energy sources—substances containing hydrogen, such as methane and water—or obtained as a by-product in chlor-alkali plants [1]. Currently, the challenge lies in the shorter technical lifespan of fuel cells compared to gas turbines, as well as the lower output power of stationary fuel cells (up to 50 MW for the largest power plants, whereas CCGT units can reach capacities exceeding 400 MW). However, it is important to highlight the possibility of harnessing additional resources from the by-product heat generated during electricity production in fuel cell operations. According to forecasts, future cost reductions for fuel cells depend on so-called technological development, which includes, among other factors, the number of implementations and the effects they bring. Assuming appropriate efforts toward optimization, the CAPEX for hydrogen fuel cells could drop to 425 USD/kW by 2030 [13]. Fuels based on compounds composed of hydrogen atoms (pure hydrogen) as well as fuels containing other elements (ammonia) could provide low-emission flexibility for power systems, directly proportional to the increasing share of variable renewable energy. It is worth noting that an alternative to hydrogen fuel is offered by power plants fired with natural gas or biogas equipped with CCUS, but they require additional investment in CO_2 capture equipment, which raises the cost per unit of power. Assuming a low load factor, hydrogen is therefore an unbeatable alternative when compared to arguments citing increased costs for natural gas with CCS and biogas. According to the chart below, it is possible to carry out a calculation, for example, with a 15% load factor and a natural gas price of 7 USD/MBtu (1 Btu ≈ 252 cal). In such a case, the price for CO_2 emissions should be at the level of 100 USD/t to consider hydrogen competitive against natural gas, because in such a scenario, the cost of producing energy from hydrogen would be 1.5 USD/kg. However, if the price of hydrogen increases by 0.5 USD, the CO_2 emission price would have to rise to 175 USD/t to maintain hydrogen's competitiveness against natural gas [13]).



3. Standardized electricity generation costs for natural gas and hydrogen load balancing
GT - gas turbine; CCGT - combined cycle gas turbine; FC - fuel cell; NG - natural gas. CAPEX - USD 500/kW GT, USD 1000/kW CCGT without CCS and hydrogen-fired CCGT, USD 1000/kW FC. Gross efficiencies (LHV) - 42% GT, 61% CCGT without CCS and hydrogen-fired CCGT, 55% FC. Economic life - 25 years for GT and CCGT, 20 years for FC. Efficiency factor - 15%. [24]

However, as the authors of this article, we personally favor a different approach regarding the profitability of investments in hydrogen. Assuming we treat hydrogen as a way to balance the unpredictability of absorption by the renewable energy grid (RES), and taking into account the construction costs (see Tab. **1**) of a 1 MW wind power plant at EUR 1.3 million with a 30% capacity factor (1×0.3×24×365=2628 MWh), the costs are as follows: for an MC 500 NEL electrolyzer with a capacity of 2.5 MW, the amount of energy required to produce 1 m³ of hydrogen is 4.53 kWh; the maximum flow rate is 492 m³/h, thus the energy demand is 2.2 MWh, meaning that with a 30% capacity factor, its installed capacity should be 7.33 MW. The construction cost would therefore be PLN 42 million, while the cost of the electrolyzer would be PLN 15,952,000. The annual operating cost of the wind farm, according to the BVEF, is EUR 19,200 per MW, which amounts to PLN 620,600 for the assumed installation. Water costs amount to PLN 20 per m³, or PLN 24,000 annually. The electrolyzer's operating cost (according to the manufacturer's data) is PLN 798,000 per year. Thus, assuming a 20-year lifespan guaranteed by the manufacturer for the installation, the marginal price of hydrogen along with the power plant is PLN 1.03 per m³ of hydrogen, i.e., approximately PLN 11.19 per 1 kg of hydrogen. However, if one assumes that hydrogen serves as a storage medium for RES energy that cannot be used by the grid—meaning its value is zero (we would exclude wind power plant costs from the above analysis)—the price for 1 m³ of hydrogen would be approximately PLN 0.52, i.e., PLN 5.78 per 1 kg of pure hydrogen. The EUR exchange rate used for the above calculations is the average NBP exchange rate from August 1, 2023, amounting to PLN 4.41.

Milestones on Egypt's Path to Restructuring Its Energy Sector Toward a Hydrogen Energy Hub

Hydrogen has long been perceived as a valuable commodity gas and chemical feedstock used mainly in oil refining and fertilizer production. Despite the timeliness of this issue, the Egyptian government did not prioritize the development of hydrogen-based energy sources until 2021, due to a lack of development plans, lack of access to technology, and high capital costs [2]. However, in August 2021, Siemens Energy and the Egyptian Electricity Holding Company (EEHC) signed a memorandum of understanding regarding the creation of a hydrogen-based industry in Egypt. Siemens Energy and EEHC will develop a pilot project featuring an electrolyzer with a capacity of 100–200 MW, which will facilitate the early adoption of the technology, as well as establish and test regulatory environments and certifications to enable expansion plans (Siemens-energy, 2021).

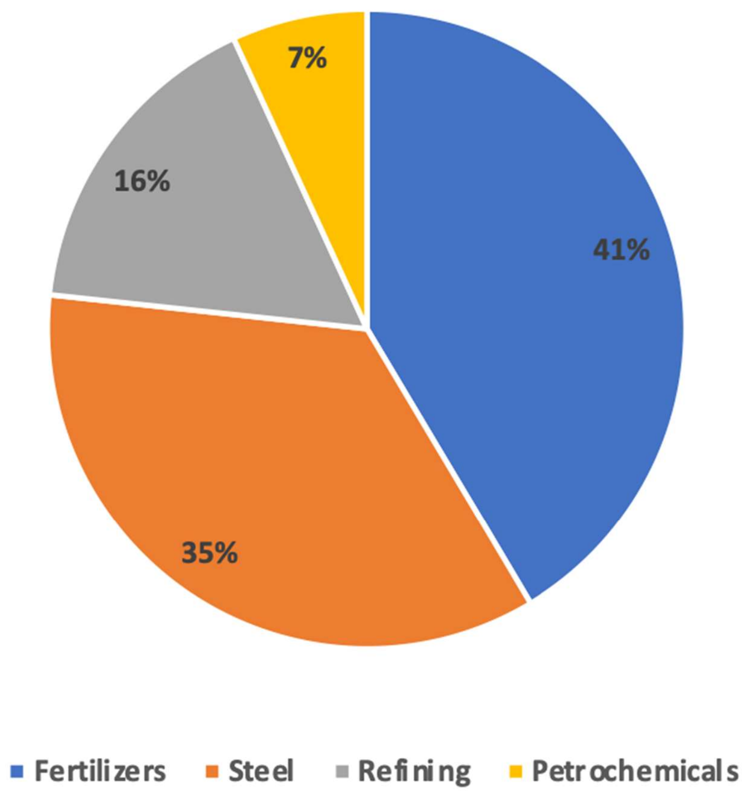
In November 2022, Egypt signed eight framework agreements to develop projects enabling the use of hydrogen and ammonia for energy production, aiming to establish a hydrogen production hub in the country and capture 5% of the global market by 2040 [19]. The agreements, signed at the COP27 climate summit with AMEA Power, Alfanar, TotalEnergies, Globeleq, EDF, Fortescue Future Industries (FFI), ReNew, and Scatec, focus on the Red Sea port of Ain Sokhna and the Suez Canal Economic Zone (Reuters, 2022). Egypt's adopted strategy includes the use of ammonia and methanol as the main sources of hydrogen production necessary to meet the country's projected demand for this resource. They could serve as fuels for maritime shipping, aviation, rail, and road transport, thus also enabling energy exports. However, shortcomings of this solution were noted at the planning stage, namely the shortage of freshwater needed for production processes. Another barrier is the distance (also defined spatially) between the place of green hydrogen production and the target location of its use. This implies higher transportation costs, forcing the restructuring of the transport sector and the need to export hydrogen via suitably adapted seaports.

Noteworthy are the agreements that enabled the creation of the Suez Canal Economic Zone (utilizing green hydrogen), valued at USD 8 billion. Another example is the renewable energy project called Alfanar, valued at an estimated USD 3.5 billion. Alfanar was implemented by Egypt in cooperation with Saudi Arabia, aiming to produce energy from green ammonia. Considering the above achievements in the area of renewable energy, it is difficult not to draw several conclusions. It seems necessary to optimize hydrogen production costs to maintain the competitiveness of the adopted solutions. Another issue is to generate a favorable case for hydrogen usage—despite the costs involved—as the foundation for transforming the energy sector to reduce emissions of gases harmful to the natural environment.

Within this framework, the European Bank for Reconstruction and Development (EBRD) granted an equity loan of up to USD 80 million to Egypt Green Hydrogen S.A.E, aimed at ensuring the development and operation of the first green hydrogen production facility in Egypt [16]. This loan is intended to help finance the purchase and installation of a 100 MW electrolyzer along with related facilities needed to develop the project in question. Decision-makers responsible for the project's success assume the greatest possible optimization to maximize the potential positive impacts of using hydrogen as an energy resource.

The electrolyzer, powered by renewable energy, will produce green hydrogen that will replace part of the hydrogen produced from natural gas used by the Egyptian Fertilizer Company and will be used as a feedstock for green ammonia production. According to the adopted assumptions, the latter will be exported to international markets [16]. This is a key step toward moving the country in the direction of decarbonizing several industrial sectors, particularly the fertilizer industry—the primary industry leading to ammonia consumption. It will be the first project of its kind in Egypt. Its success will contribute to demonstrating, more effectively than ever before, the advantages and benefits of using such a solution, representing a significant breakthrough in the development of Egypt's green hydrogen industry. The solution financed through the mentioned loan is completely environmentally friendly, as it supports the construction of an electrolyzer powered by renewable energy. Annually, it is estimated that up to 15,000 tons of green hydrogen could be produced and sold to a Fertiglobe subsidiary in Egypt for green ammonia production, corresponding to a total reduction in CO_2

emissions of over 130,000 tons per year. The European Bank for Reconstruction and Development supports the Egyptian government in developing a national hydrogen strategy [16]. An open issue remains the use of ammonia in production, accounting for about 1.8% of global carbon dioxide (CO_2) emissions. Given the need to reduce CO_2, limiting ammonia consumption must be imperative. The use of green hydrogen in the production of artificial fertilizers will save over 130,000 tons of CO_2 emissions annually (EBRD, 2023).



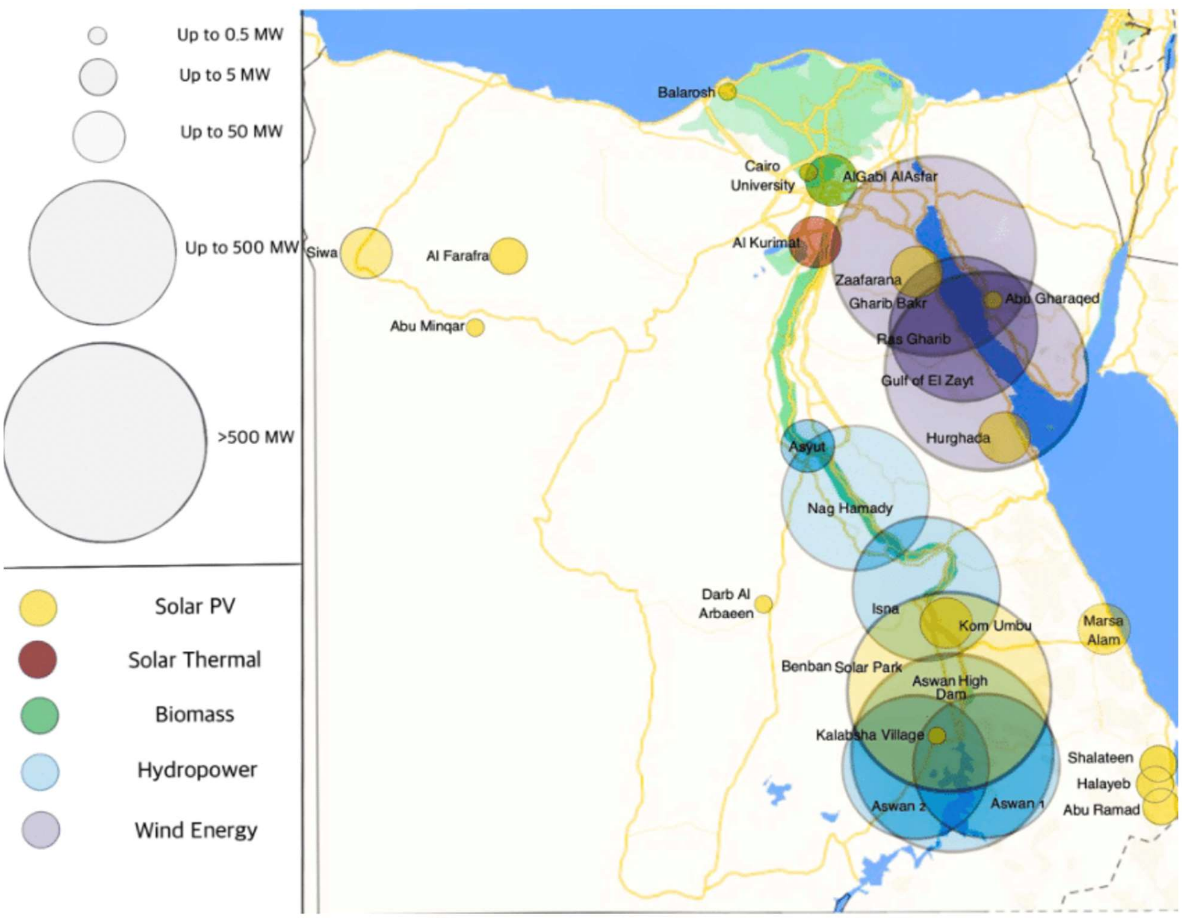
4. Estimated sectoral breakdown of current hydrogen consumption in Egypt in 2020 [25]

According to the chart above, most of the hydrogen used in Egypt was consumed in the production of artificial fertilizers, emphasizing the necessity of reducing the share of hydrogen derived from burning natural gas in favor of green hydrogen. This would consequently have a significant impact on reducing greenhouse gas emissions, underscoring the gravity of the presented investment plans.

Implementation of Plans for the Development of Hydrogen Energy in Egypt

At the beginning of March 2023, Egyptian Prime Minister Mostafa Madbouly called for a rapid announcement of an incentive package to activate all agreed arrangements and encourage investors to increase their investments in this sector, according to a statement from the Cabinet. According to Prime Minister Mostafa Madbouly, Egypt has the potential to install around 350 gigawatts of wind energy and about 650 gigawatts of solar power. In the coming years, Egypt intends to reduce carbon dioxide emissions, promote the use of renewable energy sources, and employ alternative forms of energy—including green hydrogen—within its National Climate Strategy 2050. Earlier government statements predict the possibility of producing green hydrogen in Egypt at the lowest costs in the world, at USD 1.7 per kg by 2050, compared to USD 2.7 per kg in 2025. Under optimistic assumptions, this would make it feasible to implement an ambitious plan to capture 8% of the global hydrogen market, which Egypt has already announced. The presented strategy aims to increase Egypt's Gross Domestic Product to USD 18 billion by 2050, implying an increase in employment and a reduction in oil imports.

As part of expanding its development projects, the government discussed the status of agreements and memoranda of understanding signed with several of the aforementioned international companies to undertake green hydrogen production projects in Egypt and achieve an 8% share of the global hydrogen market. Hydrogen is a proven alternative for mitigating global warming and achieving the United Nations Sustainable Development Goals. The introduction of large-scale hybrid solutions is an approach that accelerates the necessary long-term energy transformation [3]. Moreover, Prime Minister Mostafa Madbouly, during a meeting with Mohammed Shaker (Minister of Electricity and Renewable Energy) and Hala Al-Saeed (Minister of Planning and Economic Development), emphasized the need to ensure the allocation of financial resources required for the implementation of targeted projects to support the development of the initiated projects. During the meeting, the



Minister of Electricity reviewed the actions taken by the ministry in this area.

5. Projected renewable energy locations in Egypt in 2022 [26]

Egypt: A Modern Railway Project as a Continuation of Changes in the Energy Market

When Egyptian authorities nationalized the production and distribution of electricity in the 1960s, probably no one would have expected that nearly six decades later the country on the Nile would be building its first electrified railway line in its history. Currently, this groundbreaking infrastructure project for the North African state is in the implementation phase, and Egypt's energy market itself has undergone significant transformations in recent years, increasingly focusing on modern and eco-friendly solutions.

Over the past dozen years or so, the Egyptian authorities have consistently laid the foundations for sustainable and eco-friendly national infrastructure development, primarily based on environment-friendly technologies. During this time, numerous projects have been implemented, involving the construction and modernization of roads, railways, river regulation, and the modernization of airports and seaports. Given the fact that the transport sector accounts for 23 percent of total greenhouse gas emissions in this country—second only to the electricity generation sector—the long-maturing project to build an electrified railway has finally found the right moment for implementation.

In 2022/2023, the Islamic Development Bank (IsDB) approved over USD 344 million to finance the first phase of the Electric Express Train project in Egypt [21]. According to experts cited by national media, the implementation of this ambitious and breakthrough high-speed rail project, with an estimated total value of over USD 20 billion, is expected to benefit 25 million passengers annually. Under the assumptions adopted for the project, greenhouse gas emissions are to be reduced by about 250,000 tons over the course of one year—representing as much as 70 percent of the total CO_2 emissions generated by domestic transport. This would be a major step forward on the path to building a modern economy based on renewable energy sources, while simultaneously moving away from energy produced from hydrocarbons.

The first part of the project assumes that Ain Sokhna on the Red Sea will be connected to Marsa Matrouh and Alexandria on the Mediterranean by a 660 km railway line. In connection with the commencement of the project, Egyptian authorities have declared that it will have a significant impact on improving transport accessibility, as according to published estimates, up to 90 percent of Egyptians will gain access to rail transport. The project is also expected to contribute to the development of a more rational energy economy, without overlooking the aspect of promoting regional economic integration, education, and better crisis management capabilities. It is also worth noting that Egypt's tourism industry, which for many years has been one of the leading sectors of the national economy, will significantly benefit from this infrastructural revolution.

In its design, the electric express train will link all of Egypt's provinces. It will consist of three lines, totaling around 2,000 km in length, with 60 stations. The first line to be constructed will run from Ain Sukhna through Hadayek, Alexandria, El Alamein, and Marsa Matrouh. Its total length will be 660 km, running through 22 stations. The second and third lines, with a combined length of about 1,400 km and 35 stations, will run from Hayadek Station to Fayoum/Beni Suef-Abu Simbel, where three stations will be built over a 225-kilometer stretch, with an average distance of around 50–80 km between individual stops [22]. According to the project's assumptions, trains will travel along the new routes at speeds of up to 230 km/h. Apart from the Egyptian government and the Islamic Development Bank (IsDB), the main stakeholders in this large undertaking will be Deutsche Bahn (DB), in cooperation with the Siemens Mobility consortium. The relevant documents and agreements were signed by the participating parties in November 2022 in the Egyptian resort city of Sharm El-Sheikh, during the COP27 conference (the 27th United Nations Climate Change Conference). Under these agreements, Siemens will build the railway infrastructure and supply passenger and freight trains. It will also be responsible for the implementation of railway systems and power, electrical, and pneumatic networks, as well as for providing signaling, communication, and control solutions. Meanwhile, Egypt's Ministry of Transport, represented by the National Authority for Tunnels, signed an agreement for the implementation of the new network with a Deutsche Bahn (DB) consortium and El-Sewedi Electric, a private-sector Egyptian company.

According to specialists from the German train manufacturer, the railway project in North Africa will be the sixth-largest of its kind in the world. In their opinion, this eco-friendly infrastructure project is the most significant part of the Egyptian government's efforts to combat the effects of climate change. The first trains are expected to run on the new routes as early as 2025.

Assumptions of the Renewable Energy Utilization Project in the Polish Railway Sector, Taking into Account the Experience of Egypt's Railway Sector

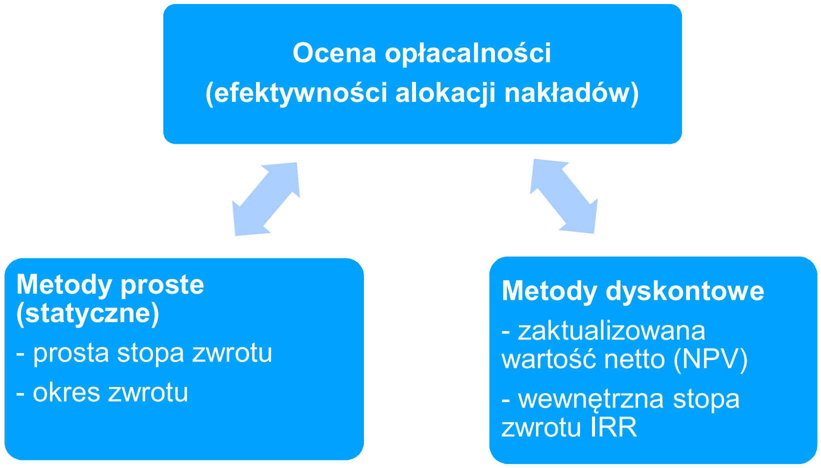
The project presented below (in the form of a table, chart, and commentary) relates to the possibility of using renewable energy sources in passenger transport through the railway sector. Considering both Egyptian and European (German railways) experiences in this regard, it must be concluded that the future of rail transport will be based on new energy carriers. Below, the basic criteria and parameters are outlined to evaluate the economics of the (sketch-based) project, taking into account, in the authors' opinion, the most important variables.

Tab.1. Assumptions adopted for the project

	Values in thousands PLN			
	Annual cost with the power plant	%	Annual cost without the power plant	%
Construction of wind farm PLN 42 million (depreciation)	2.100,0	48,4		0,0
Operating cost of wind farm	620,6	14,3	620,6	27,7
Installation of electrolyzer PLN 16 million (depreciation)	797,6	18,4	797,6	35,6
Operating cost of electrolyzer	798,0	18,4	798,0	35,6
Water	24,0	0,6	24,0	1,1
Total costs	**4.340,2**	**100**	**2.240,2**	**100**
	Assumptions			
Lifespan of the installation (years)	20		20	
Annual hydrogen production (thousand kg)	387,9		387,9	
Price of 1 kg of hydrogen (PLN)	11,19		5,78	
Amount of hydrogen needed to travel 100 km (kg)	22,5		22,5	
Cost of driving 100 km coal (PLN)	321,00		321,00	
Cost of driving 100 km hydrogen (PLN)	251,75		130,05	
Number of km possible to travel on the produced hydrogen per year (thousand km)	1 724		1 724	
Savings on changing fuel (thousand PLN)	1.193,8		3.292,0	
Annual cash flow on the project (thousand PLN)	4.091,4		4.089,6	

Source: own study based on research and own experience A. Beroud

For the selected variant, which assumes omitting the costs of building a wind turbine in the projection, a financial analysis was prepared according to the scheme presented in Fig. 1.



6. Methods used to examine the project's efficiency Source: own study

The analysis results are presented in Table **2.**

Tab. 2. Investment profitability assessment

	Indicator	**Value**	**Indicator Interpretation**
Discount	Simple rate of return for total capital	25,6%	The results achieved in this group indicate that the investment will pay off in less than 4 years.
	Simple payback period	47 m-cy	
Simple Methods	Net present value NPV (PLN)	18 817,07	NPV was calculated for a discount factor of 10% and a period of 20 years. The value obtained means that the project is effective from an economic point of view. The profitability is higher than the assumed marginal one (10%), so the project can be implemented.
	Internal rate of return WSZ/IRR	25,28%	The project is profitable and should be implemented. Over a period of 20 years, it provides an average annual rate of return of 25.3%.

Source: own study

The analyzed project model is characterized by highly favorable parameters in terms of economic efficiency. In particular, this is due to the assumption that the electricity used to produce hydrogen comes from surplus that cannot be absorbed by the grid. The project, however, is burdened by the operating cost of servicing the wind power plant corresponding to the installed capacity of 7.33 MW. In the analysis, the cost of purchasing hydrogen-powered rolling stock has been deliberately omitted, as it is considered irrelevant to the model under study.

It is therefore not surprising that Egyptian decision-makers are turning to hydrogen as the fuel of the future. In the authors' view, the ratio of the above-mentioned costs demonstrates a lack of rationality, already in the foreseeable future, for continued operation of Egyptian railways based on the electric traction network. It would be more rational here to utilize and modernize the existing infrastructure. It should also be noted that hydrogen electrolysis technology and the availability of hydrogen rolling stock remain largely within the domain of Western countries, whereas centralized conventional systems will, in the meantime, support the growth of already significant Russian influence and consolidation of that influence on the African continent.

Summary

Hydrogen as a resource undeniably represents an opportunity for Egypt's economic development. Moreover, plans implemented in past years have been successively carried out. Despite existing challenges related to cost calculations and the financial aspect of this solution, it is indisputably necessary in the context of the need for zero-emission energy sources. Sustainable development, through efficient energy resource management, is an important pillar of cleaner production and outlines the path to achieving NET ZERO. Egypt lags behind many other countries in the adoption of renewable energy technologies. In global rankings up to 2021, it ranks thirty-first in terms of solar energy use. The use of bioenergy, geothermal, wave energy, and nuclear energy accounts for a mere 0.16% of Egypt's total electricity production, even though the potential capacity of the Egyptian energy sector is much larger in this area (Salah 2022).

Energy from green hydrogen is, therefore, an optimal solution for the development of Egypt's renewable energy sector, representing both an opportunity for economic growth and a chance to improve the share of renewable energy in Egypt in a way that benefits the country, as well as yielding tangible international benefits. It should also be noted that the lack of complete railway electrification in Egypt presents an additional opportunity for the development of this sector based on island-produced hydrogen.

This also translates into the functioning of various modes of transport, including the Egyptian railways analyzed by the authors of this publication. Notably, hydrogen usage has long since moved beyond the realm of feasibility studies to concrete solutions that are being applied across different industries and in the well-developed services sector of highly industrialized countries. In line with the thesis put forward in the article *Practical Use of Hydrogen as a Strategic Energy Carrier on the Example of the Railway Sector* [11]*,* Alstom's Coradia iLint hydrogen train consumes 22.5 kg of hydrogen per 100 km, whereas a classic electric multiple unit (EMU), assuming electricity generation from coal, would require 322 kg of coal per 100 km. The fuel cost for covering 100 km (assuming a coal price of PLN 996.60 per ton) for a train using electric traction is PLN 321. Meanwhile, if we adopt the hydrogen cost based on the calculations in this article (5.78 PLN × 22.5 kg), the fuel cost needed to cover 100 km is PLN 130.05. The assumptions and calculations made are presented in Table 1.

Source materials

[1] Maestre, V., Ortiz, A., Ortiz, I., 2021. Challenges and prospects of renewable hydrogen- based strategies for full decarbonization of stationary power applications. Renew. Sustain. Energy Rev. 152, 111628. https://doi.org/10.1016/j.rser.2021.111628.

[2] Mostafaeipour, A., Hosseini Dehshiri, S.S., Hosseini Dehshiri, S.J., Almutairi, K., Taher, R., Issakhov, A., Techato, K., 2021. A thorough analysis of renewable hydrogen projects development in Uzbekistan using MCDM methods. Int. J. Hydrogen Energy 46, 31174–31190. https://doi.org/10.1016/j. ijhydene.2021.07.046.

[3] Ogbonnaya, C., Abeykoon, C., Nasser, A., Turan, A., Ume, C.S., 2021. Prospects of integrated photovoltaic-fuel cell systems in a hydrogen economy: a comprehensive review. Energies 14. https://doi.org/10.3390/en14206827.

[4] Wiącek D., Wodór jako paliwo przyszłości, 2011

[5] Kaj S., Rosja w Afryce- Na marginesie wojny rosyjsko-ukraińskiej, zeszyty historyczne Młoda Wieś, nr.8, marzec 2023.

[6] Dina Mohamed Yousri - "The Egyptian Electricity Market: Designing a Prudent Peak Load Pricing System"
[7] Montaser, Wessam, Alaboudy, Elbaset - "Fuzzy Logic Controlled Shunt Active Power Filter for Power Quality Improvement of an Egyptian Electrical Network-Connected Wind Energy System"
[8] Egyptian Electricity Holding Company Annual Report 2020/2021
[9] Ahram Online
[10] Fast Company Middle East
[11] Beroud A., Praktyczne wykorzystanie wodoru jako strategicznego nośnika energii na przykładzie sektora kolejowego, Przegląd komunikacyjny nr 1/2023, Warszawa 2023
[12] https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-to-explore-potential-for-green-hydrogen-production-in-egypt.html
[13] https://www.cire.pl/artykuly/materialy-problemowe/154373-wodor-do-wytwarzania-i-magazynowania-energii-elektrycznej
[14] https://www.dw.com/en/hydrogen-economy-egypt-to-announce-ambitious-h2-strategy/a-63466879
[15] https://www.ebrd.com/news/2022/ebrd-supports-first-green-hydrogen-facility-in-egypt-.html
[16] https://www.ebrd.com/work-with-us/projects/psd/53558.html
[17] https://english.ahram.org.eg/NewsContent/3/16/490974/Business/Energy/Egypt-to-announce-package-of-incentives-for-green-.aspx
[18] https://www.globalconstructionreview.com/china-energy-to-build-5-1bn-green-hydrogen-plant-in-egypt/
[19] Reuters, Egipt podpisuje umowy ramowe w celu uruchomienia przemysłu wodorowego, 2022
[20] Serwis Rzeczypospolitej Polskiej, Polska w Egipcie, 2023
[21] https://egyptindependent.com/isdb-approves-344-5-mln-for-egypts-electric-express-train/
[22] https://www.rynek-kolejowy.pl/mobile/gigantyczny-kontrakt-siemensa-w-egipice-stal-sie-trzy-razy-wiekszy-108315.html
[23] https://www.researchgate.net/figure/Process-flow-scheme-of-catalytic-naphtha-reforming_fig1_244749732
[24] World Energy Outlook 2019 Part of World Energy Outlook, IEA 2019
[25] https://a9w7k6q9.stackpathcdn.com/wpcms/wp-content/uploads/2021/11/Egypts-Low-Carbon-Hydrogen-Development-Prospects-ET04.pdf
[26] https://www.researchgate.net/figure/Egypts-map-of-the-current-renewable-energy-projects-plants_fig6_36022189