TECHNICAL-ECONOMIC INVESTIGATION OF POTENTIAL OF PEM HYDROGEN TECHNOLOGY FOR DRIVING THE TRANSITION TO A LOWER CARBON PRODUCTION OF CHEMICAL INDUSTRY

Dimitar Blagoev[1], Ivan Georgiev[1], Nikolay Karev[2]

[1]*University of National and World Economy, blagoev@unwe.bg (D.B.); ivangu@abv.bg (I.G.)*
[2]*University of Chemical Technology and Metallurgy 8 Kliment Ohridski Blvd., Sofia 1797, Bulgaria nkarev@uctm.edu (N.K.)*

Received 24 July 2024
Accepted 10 November 2024 *DOI: 10.59957/jctm.v60.i1.2025.18*

ABSTRACT

The article explores the economic potential of Proton Exchange Membrane (PEM)-based electrolysis hydrogen for transitioning enterprises from the chemical industry to low-carbon production. For this purpose, previous studies in this field were studied and specific calculations were made from an economic point of view, using statistical information, two-dimensional distributions and simulation of functional dependencies and financial calculations based on specialized software. With the results in the article, it was proved that there is no economic logic for hydrogen produced based on electrolysis with electricity from the grid to be used only to store energy. Additional calculations show that it is economically efficient for use in the technological processes of chemical industry enterprises. If you are looking for an average daily difference in the price of electricity purchased from the energy network.

Keywords: *economic efficiency, hydrogen, proton exchange membrane, chemical industry.*

INTRODUCTION

Provoked by the extreme climate phenomena, temperature anomalies, severe hurricanes and drought, the scientists pay more and more attention to these abnormal climate changes. A key element in the process of climate change is the increasing amount of greenhouse gases in the atmosphere. The scientists believe that these climate processes might be decelerated by limiting the level of greenhouse gases in the atmosphere, and particularly the carbon mono- and dioxide. This can be accomplished with appropriate decarbonization of the global industry, including transportation, power engineering, construction, agriculture, etc. During the last two decades attention has been paid to the hydrogen as a potential candidate for decarbonization of the entire economy. It is the basis of the conception of so called "low-carbon hydrogen economy". However, this type of decarbonization is neither easy, nor cheap, and at the present is associated with a speculative economic efficiency.

The goal of the present investigation is to explore the potential of the Proton Exchange Membrane (PEM) technology for contribution to the processes in the chemical industry as a piece of the global puzzle of decarbonization. We are looking for its potential that is based on the economic efficiency which is determined via analysis of the technical parameters of the facilities that use PEM technology. The study is composed of three primary tasks. First, we aim to estimate the energy intensity of the Bulgarian economy and to compare the data with the average European levels, and particularly the energy intensity of the chemical industry. This is accomplished with analysis of statistical information for past periods. Second, we explore the potential of hydrogen usage in the chemical industry – oil refining and nitrogen fertilizers industry. We estimate the production cost of "different types" of hydrogen and analyze their potential utilization as an instrument for decarbonization. Similar calculations have been made by other authors [1, 2]. The third task is to determine the economic efficiency of PEM-produced hydrogen. We estimate the most probable returns of such facility for hydrogen production and utilization based on the market price of the input and output energy. To achieve our goals, we process and analyze statistical information with appropriate software tools.

Development of the chemical industry and its energy consumption

Bulgaria has (or at least had until the last decade) a well-developed chemical industry sector. It mainly includes oil refineries and nitrogen fertilizer plants. In Bulgaria, such are the oil refinery in Burgas (Lukoil Neftohim), Prista Oil in Ruse, nitrogen fertilizer plants in Dimitrovgrad (Neohim AD), Stara Zagora (Agrobiohim AD), Devnya (Agropolihim AD), Fikosota, Insa oil, etc. The chemical industry generates about 4 % of the country's GDP. The number of employed is on average between 13,000 and 14,000 people, and the number of active enterprises is around 650.

The main indicators with which we can measure and investigate the development of a given sector of the economy and on this basis for energy consumption are: Enterprises - number; Turnover; Production value; Gross margin on goods for resale; Value added at factor cost; Gross operating surplus; Total purchases of goods and services; Purchases of goods and services purchased for resale in the same condition as received; Payments for agency workers; Personnel costs; Wages and Salaries; Social security costs; Employees – number and more others.

Of course, in an article with a limited volume, we cannot examine all indicators, and we do not need to. For the purposes of this study, the indicators for 'industrial production (output)' and 'turnover', have been selected to track economic development of chemical industry sectors. These indicators are considered on an index basis, at 2015 = 100, i.e. the change in the absolute values of the variable is reported. Based on these two indicators, we will be able to draw conclusions about the trend in energy consumption by chemical enterprises.

The index of industrial production is an important indicator that shows us the direction and rate of change of the produced output for a certain period in the enterprises of the relevant sector of the national economy (Fig. 1).

The trend of the dynamics of the index of industrial production in the enterprises of the chemical industry is ascending (Fig. 1) For the observed period, a sustainable growth rate is reported. The positive change is 129 % (or from an index of 63.7 at the beginning of 2000 to an index of 145.7 in mid - 2024). There is no doubt that during the period there were a number of fluctuations provoked by various business factors and the geopolitical

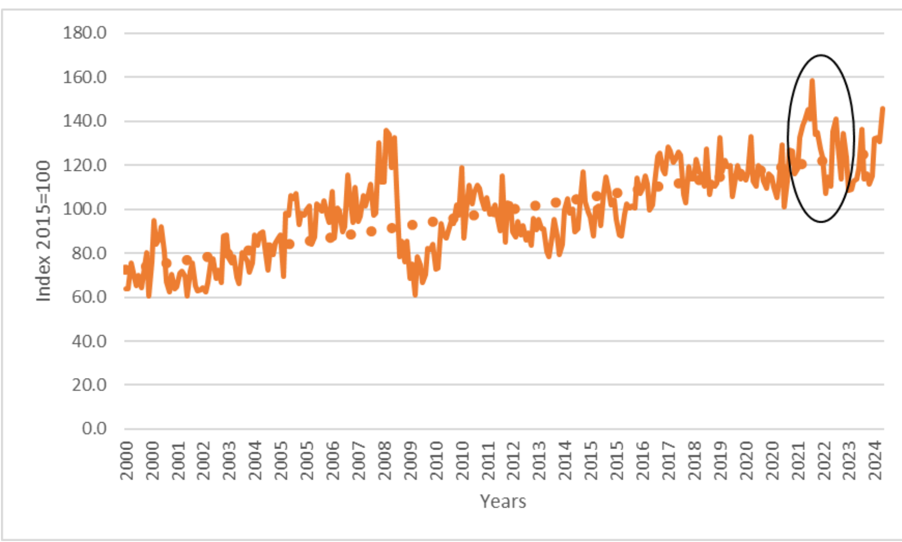

Fig. 1. Dynamic of index of industrial production in chemical and chemical products manufacture 2000-2023 [13].

environment. Two of the sharper movements in the period index can be pointed out as more serious. The first decline (after which there was a period of recovery) was during the global financial and economic crisis in 2007 - 2009. The second decline was provoked by post-Covid19 and the war in Ukraine and the Middle East in the period 2022 - 2023.

The long-term upward trend in the industrial production index can be explained by the fact that more and more fertilizers and fuels are needed by the world economy today.

Another indicator showing trends in the development of an economic sector is the industrial turnover index. If the index of industrial production shows us the volume of production produced by enterprises for a certain period in natural terms, then the index of industrial turnover shows us the same in terms of value. For the considered period chemical sector has an upward rate of change in turnover (Fig. 2).

In the chemical industry, the change in the index of industrial turnover is + 532 %, or more than 5 times (from an index of 28.4 at the beginning of 2000 to an index of 179.7 in mid - 2024). This serious increase in the turnover of enterprises in the chemical industry (and considering the upward trend of the change in the index of industrial production for the period for this industry) is due to both a serious increase in the prices of final products and of raw materials and materials necessary for chemical production, as well as the increase in the volume of production for the period. The two main crisis periods are clearly visible - the global economic crisis of 2007 - 2009 and the Covid19 pandemic reinforced by military conflicts in Ukraine and the Middle East (Fig. 2 marked areas). An interesting fact is that based on the graphs, the intensity of negative impact of the global economic crisis of 2007 - 2009 is significantly weaker than the post Covid19 pandemic and current military conflicts.

It can be said that the upward development rate of the chemical industry in Bulgaria will require more energy resources in the coming years. Therefore, the development and economic efficiency of hydrogen technologies will be important for the future development of this industrial sector.

According to the Statistical classification of economic activities in the European Community (NACE), 2008, the companies that are involved in the chemical industry of Bulgaria fall in the following sectors and subsectors (Table 1).

The activities with the biggest carbon footprint and energy consumption are those with code 19.2 and the activities of the entire group 20 (Table 1). The chemical production influences the environment and has a carbon footprint, generated mainly by utilizing some fossil fuels like natural gas for production of Hydrogen (H_2). The activities in the group with code 19 and 20 (Table 1) are

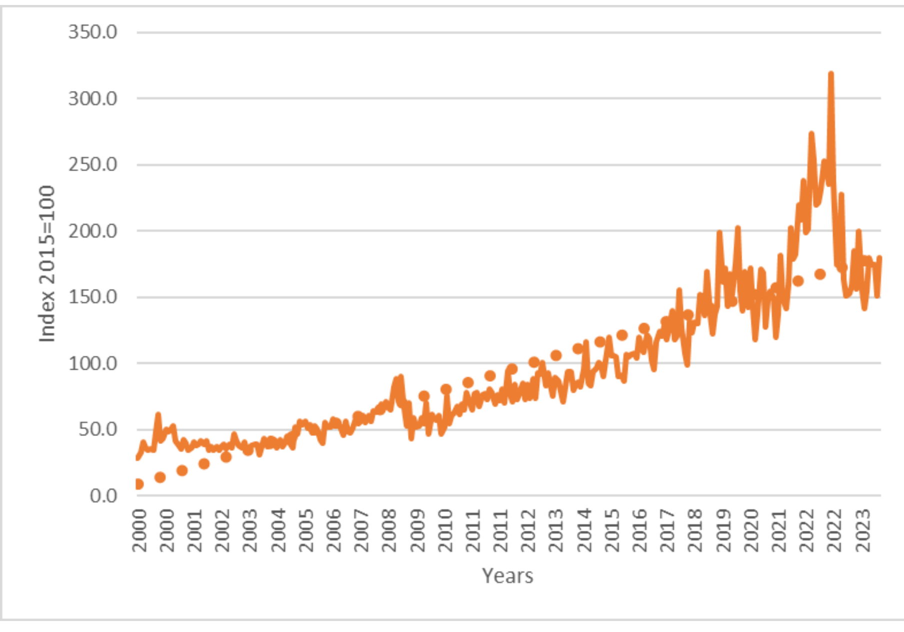

Fig. 2. Dynamic of general index of industry turnover of chemicals and chemicals products manufacture 2000 - 2023 [13].

Table 1. Economic activities of the companies in the chemical industry, NACE, Bulgaria, 2008.

Code	Economic activity
19	Production of coke and refined petroleum products
19.1	Production of coke and coking products
19.2	Production of refined petroleum products and coal, briquettes and peat
20	Production of chemical products
20.1	Production of basic chemicals
20.2	Production of pesticides and other agrochemicals
and	
23	Production of products from other non-metallic mineral raw materials
23.5	Production of cement, lime and gypsum

well-known with their energy intensity. In the present study, we aim to focus on the companies having activities that fall under the code 19.2 and 20.2 (Table 1).

Hydrogen technologies in the chemical industry

Natural gas reforming is the main contemporary process for producing of hydrogen. This process is accompanied by production of carbon monoxide (CO) and eventually carbon dioxide (CO_2) [4]. Currently, around 80 % of the total produced hydrogen is that type of hydrogen. It is being used mainly in the petroleum industry and in the production of nitrogen and nitrogen fertilizers [7].

In recent years, the strategic documents of the EU have focused mainly on the use of "green hydrogen". The definition of "green hydrogen" is made in the law of energetics. Green hydrogen is produced by electrolysis or another method, but by using energy from renewable energy sources [8].

The leading advantage of the green hydrogen is its large-scale utilization that depends only on the quantity of the available renewable energy. It can be used for storage of energy, obtained from renewable energy sources and it represents one of the very few technologies that allows season-dependent storage of energy. The most important thing is that the use of the green hydrogen is not associated with emission of greenhouse gases, and therefore there is no atmosphere pollution. In such way the green hydrogen offers a solution for decarbonization of industrial processes and economic branches which need this decarbonization, but the last is hard to achieve. All this makes the hydrogen of particular importance for the EU engagement in activities for reaching carbon neutrality by 2050 as well as for the global efforts for accomplishment of the goal of the Paris Agreement.

In the report "Assessment of the potential for development of hydrogen technologies in Bulgaria 2022", prepared by the Ministry of Innovation and growth of Bulgaria, are analyzed sectors of the Bulgarian economy, which are suitable for decarbonization via utilization of hydrogen, and the possibilities for hydrogen large-scale production [9]. The report also considers existent or potential obstacles for the adoption of the hydrogen technologies by the Bulgarian economy and the introduction of certain changes in the regulatory framework to overcome these obstacles. However, in most of the strategic documents is absent information about the economic impact of the hydrogen utilization on the future development of the companies.

Consumption of hydrogen and ammonia by the chemical industry

As mentioned above, the green hydrogen is the hydrogen that is produced via electrolysis with the utilization of energy produced by renewable sources, e.g. photovoltaic power plants, hydroelectric plants, and wind power stations. In such way and closing the hydrogen cycle "from water to water" with zero carbon emissions, this hydrogen appears suitable candidate for energy source of the industry sectors with high expenses for decarbonization activities. This also implies that green hydrogen is a reasonable constituent of the conception for "circular economy". Companies of the chemical industry uses hydrogen not only as a storage of energy, but also as a resource in their technological cycles. In the strategy for assessment of the potential for development of hydrogen-based technologies in Bulgaria 2022 it is pointed out that "…the green hydrogen is expected to become universal and sustainable energy source that could facilitate the process of energy transition, preserve the competitive power of key European industry sectors (e.g. chemical industry in Bulgaria), diminish the future needs for fossil fuels, and play an important role in the global energy map" [9]. Currently, the companies of the chemical industry in Bulgaria (oil refining companies and producers of nitrogen fertilizers) use hydrogen that is mainly obtained through the so called "steam reforming" of natural gas. This process is associated with release of carbon dioxide. That is why this technology cannot be used for decarbonization activities. According to the hydrogen ranking in terms of "colour", depending on the used production source and technology, this hydrogen represents the so called "grey hydrogen". In the above-mentioned strategic document, we can find also that "…barely 2 % of the hydrogen is produces via water electrolysis. Aim of the European hydrogen strategy by 2030 is this production to increase dramatically with installing of 130 GW electrolysers (at present they are only 1 GW). Currently, the most powerful electrolysers are 10 MW, but the development of 100 MW electrolysers is in progress)". At the same time one of the biggest consumers of hydrogen and ammonia (produced with hydrogen) are the companies of the chemical industry. These are mainly oil refining companies and producers of nitrogen fertilizers. In Bulgaria they are represented by Lukoil Neftohim Burgas PLC, and Neochim PLC, Agrobiochim PLC, Agropolychim PLC, respectively. According to aggregated data for the European Union (EU), cited by the European Free Trade Association (EFTA) and Great Britain (Clean Hydrogen Monitor, 2022), during the year 2020 more than 95 % of the capacity for hydrogen production in Europe is based on fossil fuels. Around 79 % of the total production and consumption of hydrogen and ammonia, obtained via steam reforming of natural gas, are due to the companies of the chemical industry. However, unlike the hydrogen, obtained via steam reforming of natural gas, which has high degree of carbon intensity, the green hydrogen, obtained via water electrolysis, and with the use of renewable energy sources, has low to zero degree of carbon intensity. This is the reason why the green hydrogen appears to be a key element of the energy system transformation that is associated with substitution of the natural gas, coals and other fossil fuels. The green hydrogen is also the milestone on the road to achieving the so called "carbon neutrality" of the chemical industry.

The cost price of the grey hydrogen is directly depending on the price of the natural gas. This cost price may vary as much as from 2.6 € per kg (2021) to 10 € per kg (2022). On the other hand, the cost price of the green hydrogen is around 4.5 € per kg and depends basically on the location of the production facilities, e.g. 6.3 € per kg - 10€ per kg for north countries like Great Britain and Norway, and 2.9 € per kg - 4.5 € per kg for south-located countries like Greece, Spain, Italy [10]. This is primarily a consequence of "more sunny days" that can be used for generation of photovoltaic solar energy. For Bulgaria, according to a study in 2023, the average cost price of the grey hydrogen is 6.8 € per kg. The major element of that cost price is the price of the energy source (e.g. natural gas), and much less are the expenses associated with the trading of carbon dioxide emissions. The capital expenditures (CapEx) and the operating expenses (OpEx) represent insignificant values of the total cost (TC). The average cost price of the green hydrogen, when energy from electrical grid is used, is 5.3 € per kg. Compared to the cost price of the grey hydrogen, that represents 22 % decrease. Similarly, the major element of the cost price is the price of the electricity and the electrical grid fees, and again CapEx and OpEx are of very small value. The utilization of independent photovoltaic solar energy for production of green hydrogen saves some resources and/or expenses (e.g. electrical grid fees) but rises the cost price of the green hydrogen because of the initial investment expenses for building of the photovoltaic power stations to supply the green hydrogen production facilities. The financial expenses could further burden the construction of photovoltaic power stations. In this case the cost price of the green hydrogen, produced in Bulgaria, could become 43 % more expensive (up to 7.6 € per kg), and even more expensive than the grey hydrogen (around 12 %, see above) [11].

Conforming to an annual survey for the production and consumption trends of hydrogen in EU, it is expected that the ratio of green hydrogen to grey hydrogen would be 1.22 by 2030 [11]. On the other hand, there is no available data or any public plan for production and consumption of green hydrogen by 2030 in Bulgaria.

The brief analysis made above shows that, if obtained via private photovoltaic power stations, the green hydrogen is not cost-effective. The electrolyser facilities of the companies of chemical industry may produce green hydrogen for their own technological needs, but the chemical sector may also utilize it as a storage of energy. In this respect, of particular interest could be the exploration for eventual short-term differences in the price of the energy from electrical grid, which can be used for substantial optimization of the green hydrogen production and usage, e.g. the green hydrogen can be produced with low-cost electricity and used or sold in the form of energy when the price of that electricity is higher. We also would like to note that the chemical industry is an energy-intensive industry.

The averaged data for the market price of the electricity (MW h) at the Independent Bulgarian Energy Exchange (IBEX), listed in the market segment "Day ahead", shows significant fluctuations across the different parts of the day (Fig. 3). These fluctuations, respectively, are dependent on the specifics of the supply, demand, seasonality or other particular climate-relevant circumstances.

Based on the data in Fig. 3, we can differentiate two price-specific and discrete periods - (i) period of low relative prices, which comprises hours between 22:00 and 06:00, and hours between 10:00 and 17:00, and (ii) period of high relative prices, which comprises hours between 6:00 and 10:00, and hours between 17:00 and 22:00. The average electricity price in these two price-specific periods is 63.9 € and 125.3 € per MW h, respectively, which represents a two-fold increase in the price. We use these two values of the average electricity price to determine the cost-effectiveness of a hydrogen electrolyser facility in the companies of the chemical industry, and the analysis is based on the assumption made above - green hydrogen production and storage during the low price-specific period, and green hydrogen utilization during the high price-specific period.

Technical characteristics of hydrogen and electricity production installations

Installations for the production of hydrogen and electricity from hydrogen in enterprises of the chemical industry must consist of the following elements (utilities): (1) module for the production of hydrogen by electrolysis; (2) module for the storage of hydrogen; (3) module for the production of electric energy from hydrogen, and (4) auxiliary (service) infrastructure. These facilities are expected to support the achieving of much lower carbon footprint via generation and proper utilization of hydrogen.

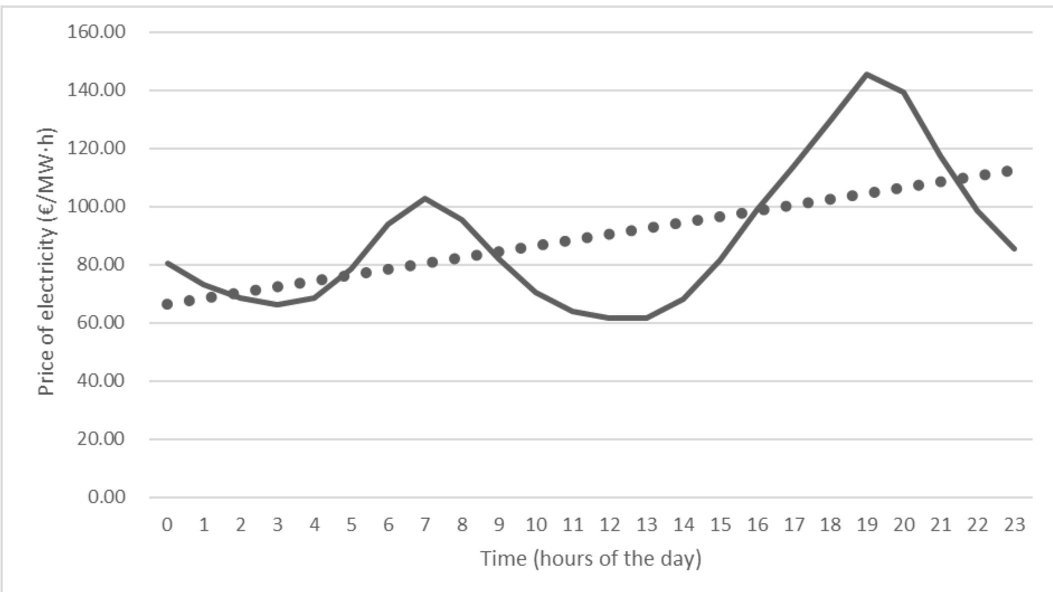

Fig. 3. The averaged data for the market price in € of the electricity (MW h) at Independent Bulgarian Energy Exchange (IBEX) [14].

Module for the production of hydrogen by electrolysis

The electrolysis is a method of producing hydrogen from water by using electrical energy to split the water molecule into hydrogen and oxygen. For the purposes of our simulation, we will use proton exchange membrane (PEM) electrolyzer - an equivalent of "GINER S400" with power 2.1 MW. 5 (five) container-type electrolyzers are provided.

Module for the storage of hydrogen

The hydrogen storage module will have a capacity of 100 000 m^3. It will be built from 68 tanks with a storage capacity of 50 m^3 at a pressure of 4.0 MPa of hydrogen in them.

Module for the production of electric energy from hydrogen

The production of electric energy from hydrogen will be carried out by fuel cells equivalent to "HYDROGENICS" with a capacity of 1MW. For the purposes of our simulation, 5 such modular type fuel cells will be used.

Auxiliary facilities and buildings

To be a complete, a given hydrogen facility needs some auxiliary facilities, such as: (i) water facilities - pumping stations and sewer system; (2) gas facilities - nitrogen and compressor facilities; (3) other auxiliary facilities - buildings, storages, etc.

Stages of the evaluation of the economic efficiency of the production of hydrogen and of electric energy from hydrogen (methodological aspects)

Goals of the analysis and the assessment

- To define main parameters from economic point of view of a hydrogen facility with basic power of 5 MW: economic life, production schedule (for a year), cash flows (investments and net income)
- To calculate main financial indicators for assessment of the economic life and the effectiveness of the hydrogen utilization for satisfying the energy needs of the chemical industry enterprises.
- To draw reasonable and economically justified conclusions regarding the potential of the hydrogen utilization for decarbonization of the activities of the chemical industry enterprises.

The process of evaluating the economic efficiency of such an installation for the production of hydrogen and subsequently of electric energy from hydrogen includes the following stages: (1) Determination of the volume of investment costs and their distribution by types - direct investments, accompanying investments, related investments, etc.; (2) Development of a production program - for the production of hydrogen and for the production of electric energy from hydrogen; (3) Determination of operational (current) production costs - of hydrogen and electricity; (4) Calculation of the income generated from sales of the electric energy that is not used for private consumption; (5) Determining the sources of funding and the weighted average cost of capital the entire investment; (6) Calculation of main indicators for evaluating the economic efficiency of the investment.

The simulation input variables are as follows: Period of economic life - 23 years (construction 3 years and exploitation 20 years); Electric power supply - 11 MW, power of the electrolyzers - 2 MW, volume of the stored hydrogen - 100 000 Nm^3, weighted average cost of capital - 5 %, selling price of the electric energy (averaged data for one year for the lowest price per megawatt on the Independent Bulgarian Energy Exchange, specified in point 3 of the article), generation of electric energy - 5 MW h^{-1}, initial investments, income from potential "sales" (averaged data for one year for the highest price per megawatt on the Independent Bulgarian Energy Exchange, specified in point 3 of the article), etc.

For the purposes of evaluating the economic efficiency of the investment, we will use the following main indicators:

Net Present Value (NPV)

$$NPV = -\sum_{t=0}^{m} \frac{Co_t}{(1+r)^t} + \sum_{t=m+1}^{n} \frac{Ci_t}{(1+r)^t}, \qquad (1)$$

where: Co_t is the investment expenses in Bulgarian currency, leva, (cash outflows), realized in the first years of the economic life $(t = \overline{0, m},\ m \in n)$;

Ci_t is the net income in Bulgarian currency, leva, (cash inflows) in the tth year of operation of the facility $(t = \overline{m+1, n})$; r is the rate of return, used in the present discounted value. In the case under consideration, this is the cost of capital of the new facility.

$$ARR = \frac{\text{Average operating income}}{\text{Average book value of assets}} . 100, \%$$

Return on investment (ROI)

$$ROI = \frac{\text{Operating income (for year, non} - \text{discounted)}}{\text{Total invested capital}} . 100, \%$$

Internal Rate of Return (IRR)

$$0 = -\sum_{t=0}^{m} \frac{Co_t}{(1 + IRR)^t} + \sum_{t=m+1}^{n} \frac{Ci_t}{(1 + IRR)^t}$$

Parameter symbols are the same as in equation (1).

The selected indicators for evaluating the economic efficiency of the investment are appropriate and reflect the technical and economic specifics of investing in such industrial facilities.

RESULTS AND DISCUSSION

Investment expenses for construction of hydrogen facility with power of 5 MW (Table 2).

Production schedule (Table 3)

Production expenses

The electric energy for generation of the hydrogen will come from grid and will have minimal cost of 63,9 € per MW h. There will be additional expenses for labour and production operating costs. The total expenses will be 4 611 991 € per year.

Evaluation of the potential benefits (income) of the generated electric energy from the hydrogen

The income from such an investment can be generated from the sale of the produced electricity for one year. The forecast price at which electricity will be

Table 2. Initial investments.

Type of investment expenses	Sum in Euro (€)
Direct investments	22 081 170
Investments in working capital	436 510
Total	22 517 680

Table 3. Production program.

Variable	Unit of measurement	Value
Generation of hydrogen		
Electrolysers	number	5
Generation of hydrogen per hour	$Nm^3\ h^{-1}$	400
Generation of hydrogen of all electrolysers per hour	$Nm^3\ h^{-1}$	2000
Storage of hydrogen		
Reservoirs	number	68
Volume of a single reservoir	m^3	50
Pressure in the reservoir	MPa	4
Total volume of stored hydrogen	m^3	100640
Time for filling of all reservoirs	hours	50.32
Generation of electricity		
Number of generators of electricity	number	5
Output power of the generator	MW	1
Hydrogen consumption for generation of 1MW·h electric energy	$N\ m^3$	750
Hydrogen consumption for all generators per 1 hour	$N\ m^3$	3750
Generator worktime for a cycle (one emptying of the reservoir tanks)	h	28
Generated electric energy per cycle	MW h	134
Number of cycles per year	number	114
Generated electric energy per year	MW h	15 235

Table 4. Indicators for economic evaluation.

Indicator	Unit of measurement	Value
Net present value (NPV)	Euro (€)	- 48 504 703
Return on investment (ROI)	%	-10.8
Accounting rate of return (ARR)	%	-14
Internal rate of return (IRR)	%	n.a.
Profitability index (PI)	number	-1.29

sold can be determined from the retrospective data on the price of electricity on the Bulgarian Independent Energy Exchange. For the purposes of our simulation, we divide the exploitation period into two 10-year sub-periods. In the first, we predict the price of electricity to be €125.3 per MW h, and in the second, €153.3 per MW h. Based on this price and on the basis of the developed production program for the production of electrical energy during the period of operation, the undiscounted income for the first sub-period will be 1 908 407 € per year, and for the second sub-period 2 336 826 € per year.

Funding and the cost of capital

The funding is 22 517 680 € and has a weighted average cost of capital 5 %. It reflects both the minimum yield rate for the investors and the cost of the potential investment bank credits.

Indicators for economic evaluation of the investment

The data are summarized in Table 4.

CONCLUSIONS

From the calculated indicators for evaluating the economic efficiency, we can conclude that the investment in the considered hydrogen facility is economically unfeasible if we will use the produced hydrogen only as a tool for energy storage. Besides the wanted economic efficiency, such investment would have environmentally friendly ecological effects.

All the calculated indicators have negative values (Table 4). The NPV shows that the pure economic effect for a period of 20 years would be negative - 48 504 703 €, and the PI value shows that for every invested lev we will lose another 1,29 €.

All these results assume that the electric energy, obtained from grid, and used to power the electrolysers for the generation of hydrogen, is of price 63.9 € per MW h during these 20 years. If the economic conditions appear to be different, the obtained results will be different too.

Our study shows that there lacks cost-effectiveness if the green hydrogen, produced with the energy from electrical grid, is used only as a storage of energy. The analysis demonstrates that the process is cost-effective if the green hydrogen is further and promptly used to provide energy for the technological operations in the chemical industry. Considering the technical parameters of the suggested electrolysers and the average daily electricity price of IBEX for the low price-specific period, we indicate that the cost price of the green hydrogen, calculated only on the basis of the energy expenses for production, is 3.9 € per kg. Considering the data from Hydrogen Europe (see the respective references), which focuses on the value of 5.3 € per kg (see above), we can assert that our study apparently gives lower and “more optimistic” price value. If we recall that CapEx and OpEx represent insignificant part of TC, these expenses would not generally influence the calculated cost price of 3.9 € per kg.

Acknowledgements

We acknowledge the financial support of the project “Research and Development of a Conceptual Model of an Academic Innovation-based Incubator”, №NID NI-3/0222/A, R&D Fund, University of National and World Economy, Sofia, Bulgaria.

Authors’ contributions: All authors contributed equally to the preparation of the study.

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