Multi-criteria Approach to Justification of Production Technology of Hydrogen Fuel

Nikolay K. Topuzov, Andrey E. Shchelkonogov, and Ivan S. Amelin

***Abstract*—The paper analyzes the existing problems of depletion of fossil fuels and alternative fuels, viewed as a substitute for fossil ones. The post-carbon energy is largely determined by the technology of producing alternative fuels. The multi-criteria approach to the choice of the technology of producing hydrogen fuel is based on the search for hybrid technologies on a competitive basis. Based on the integral-matrix analysis the need for the search of hybrid technologies for competitiveness of producing the hydrogen fuel is substantiated. The studied selection of production technology of the hydrogen fuel meets the stated criteria more fully, taking into account the development trends of three areas: market, technology and product.**

***Index Terms*—Production technology, hydrogen fuel, electrochemical decomposition of water, integral-matrix analysis, multi-criteria approach**

I. Introduction

THE extensive development of the modern industrial and transport infrastructure has been implemented largely due to the availability of affordable energy carriers based on the carbon resources, providing heat and electricity to consumers virtually all over the world.

The use of carbon resources in power systems and transport infrastructure not only leads to obvious advantages due to their wide distribution, debugged technological processes of their production and usage, but also significant disadvantages, whose manifestation can be observed in the ecosystem of the planet as the growth of the techno-genetic load.

The side effects of using carbon fuels are:

– violation of the hydrogeological regime, groundwater contamination and soil erosion in the field of fossil fuel production;

– air pollution by oxides of carbon, nitrogen and sulfur, by soot, heavy elements, hydrocarbons;

– violation of the atmosphere heat balance and the increasing greenhouse effect due to the emission of man-made heat and other by-products at power stations.

The result of the influence of these factors is a series of negative events, such as the melting of the ice sheets, the growth of the average planet temperatures, the growth of financial losses due to reducing the negative impact on the ecosystem and a number of others.

To prevent the increase in emissions from industrial facilities and transport infrastructure, the following methods are used: modernization of waste gases treatment systems at industrial facilities and transport [7]; synthesis of fuel additives reducing fuel combustion emissions and fuel consumption [8]; development of alternative fuels with improved technical and economic properties [4]. The emissions reduction strategy at fossil fuel combustion due to consumption optimizing systems lets insignificantly reduce the amount of carbon and sulfur oxides, soot in the waste gases. However, the emission reduction results are offset by the growing number of vehicles and industrial plants. As a result of this situation, there is an intensive consumption of fossil resources, which are becoming more valuable because of the reduction of their inventories. So, according to various forecasts the world's volumes of the proven oil reserves will be depleted in the next 70 years [9].

Thus, the optimization of strategy of the carbon energy resources consumption cannot be chosen as primary with the further technological development as inevitably leads to the formation of the substances polluting the planet's ecosystem and the depletion of the limited fuel resources, and can be considered as an interim measure for the period of developing the alternative fuels.

The financial and economic aspects of transition to alternative fuels are the most important. The comparison of the production cost of a hydrocarbon fuel unit, such as gasoline, and the cost of a unit of the most available alternative fuels, such as methanol, reveals the obvious more than twice advantage of the alternative fuel. This financial advantage is supported by the following fact: at determining the cost of fossil raw materials there is no accounting of financial flows on a number of events of global proportions, the purpose of which is the reduction and compensation for the destructive impact of the production and consumption of carbon fuels on the ecosystem of the planet [2]. Only in Russia in the period from 2013 to 2016 the environmental protection expenditures increased by about 25 % [1]. As a result, the alternative energy resources due to the weak environmental impact, along with the possibility of a low-cost production, are becoming an attractive substitute for the carbon energy.

The search for an alternative energy source of began in the early 20th century, and it was especially intensive during

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World War II. At the moment, the following types of alternative energy carriers have been derived and approved: methanol, ethanol, natural gas, biogas, hydrogen [11].

Among the alternative energy resources hydrogen is the most controversial candidate for the title of an effective substitute for carbon fuels [3].

Numerous scientific publications on the hydrogen energy separate the two basic positions for the use of hydrogen as a future energy source: supporters and opponents of the hydrogen energy. The main causes that lead to the divergence of views on the massive use of hydrogen in the energy and transport infrastructure, is the presence of negative factors hindering the process of hydrogen development as a fuel, as well as a number of its properties, forming specific requirements for its production, storage and consumption.

TABLE I
CHARACTERISTICS OF THE HYDROGEN FUEL FOR ENERGY AND TRANSPORT SYSTEMS

Positive properties	Negative properties
▪ lack of atmosphere pollutants in use; ▪ large calorific value as compared to the gasoline fuel (3 times); ▪ combustion heat 13–14 times less as compared to the gasoline fuel; ▪ possibility of obtaining in an unlimited scale; ▪ possibility of adapting the traditional internal combustion engines for the use of hydrogen; ▪ savings on feed for the production of hydrogen fuel; ▪ possibility of electrochemical power production in fuel cells with high efficiency	• energy-intensive production; • high diffusion capacity with respect to most materials; • high explosiveness of the hydrogen mixed with air; • low density; • reducing the ICE power at the use of hydrogen; • high evaporation losses; • energy-intensive process of compressing and storage

Currently, large volumes of hydrogen are used as an intermediate product in the petrochemical and oil refining industries. This approach is largely due to the high cost of hydrogen production and storage, forcing large industrial enterprises to organize local production of hydrogen to be used exclusively for their own needs. As a result of the existing approach the mass market of the commercial hydrogen has been poorly developed and is represented mainly by the enterprises selling it in small volumes on a special order.

The trends of consuming the fuel and energy resources are inevitably leading to deterioration of the ecological situation and drastic reduction of the carbon energy carriers. On this basis, most experts agree that in the nearest future there will be a significant growth in consumption of alternative fuels, such as hydrogen (Fig).

The hydrogen consumption growth will require reduction in energy and financial costs of its production by the available methods. At the moment there are following widespread hydrogen production methods: coal gasification, steam reforming of methane, coke oven gas fractional liquefaction, electrolysis of aqueous solutions. There appears a choice problem of technology for producing hydrogen, satisfying environmental and financial requirements, that is to minimize the impact on the environment in the process of hydrogen production and reduce the cost of the technological process. To ground the reasonable choice of the hydrogen fuel production technology the paper applies the integral-matrix analysis (IMA) allowing a multivariate analysis in three areas (market, technology, product) based on the relationship of the strategic and operational objectives for the development of the final product [5].

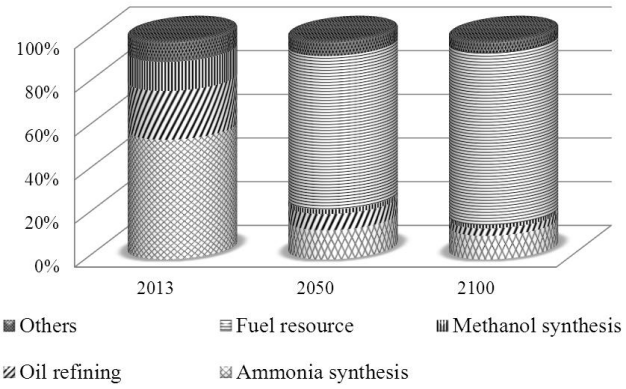

Fig. Dynamics of the consumption structure of hydrogen

As part of the integrated-matrix analysis the operational objectives, reflecting the activities to be carried out in the short-term period (the current state of the object), and the strategic objectives defining the desired state of the object in the long-term period, were applied.

Forming strategic and operational objectives for the selection of the hydrogen fuel technology through the integrated-matrix and expert analyses was conducted by an expert focus group of the SUSU and the Fortum energy system specialists.

II. INTEGRAL-MATRIX ANALYSIS OF STRATEGIC AND OPERATIONAL OBJECTIVES OF THE HYDROGEN ENERGY

TABLE II
STRATEGIC DEVELOPMENT OBJECTIVES OF THE HYDROGEN ENERGY

Strategic objectives	Market (YC)	Technologies (XC)	Product (ZC)
	Reduction of the hydrogen fuel production costs to the level of alternative analogues	Reducing the energy consumption of the hydrogen fuel production process	Development of the service infrastructure of the hydrogen production facilities and vehicles on the hydrogen fuel
	Increasing the share of hydrogen fuel consumers	Hydrogen fuel production transition to the renewable raw materials and energy carriers	High performance the hydrogen fuel production facilities per unit of the raw material
	Forming the state supportive system of manufacturers of the hydrogen fuel production equipment and its components to reduce the fuel cost	Creating the long portable hydrogen storage systems with minimal diffusion losses	Long turnaround time of the installations for the hydrogen fuel production and use
	Creating a network of suppliers and users of the commercial hydrogen based on the petrochemical and energy fields	Development of the hydrogen fuel storage and delivery infrastructure to large consumers	Creating the hydrogen fuel long-term safe storage system in a vehicle and in the generating capacity areas
	Forming the logistic schemes of interaction between suppliers and consumers of hydrogen	Upgrading the hydrogen fuel production and use systems for increasing the efficiency and simplifying the manufacturing process	High degree of the produced hydrogen purity

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To achieve these objectives as part of the development of the hydrogen power industry it is necessary to solve a number of current issues, reflected in the form of operational tasks.

TABLE III
OPERATIONAL DEVELOPMENT OBJECTIVES OF THE HYDROGEN ENERGY

	Market (YO)	Technologies (XO)	Product (ZO)
Operational objectives	Introduction of hydrogen as an additive to fossil fuel to increase its demand	Adaptation of the present nanomaterials for use in the hydrogen fuel storage and production systems	Application of composite materials, alloy steels in the hydrogen production, storage and use systems; minimization of moving parts, improving the heat balance
	Attraction of capacities of petrochemical, energy and oil refining enterprises to produce hydrogen	Development and introduction of catalysts, accelerating the process of hydrogen production, reducing energy consumption	The use of materials, additives that increase the flow rate of the hydrogen production reaction, reducing losses of raw materials and by-products
	Consolidation of efforts of automobile companies for working on fuel cells and hydrogen production technologies by forming joint research centers	Use of reserve capacities of power plants to produce hydrogen fuel [10]	Use of additives to the hydrogen fuel and sensors to prevent formation of explosive oxyhydrogen gas
	Creation of the commercial hydrogen market development program to raise state support and investors funds	Replacement of precious metals and other expensive components in the hydrogen fuel production systems by cheaper ones	Modernization of the hydrogen purification technological processes and using methods of hydrogen production with the highest degree of purity
	Attraction of cheap electricity (nuclear, hydro power stations) for the hydrogen fuel production	Upgrading the fuel systems of vehicles and generating capacities for using hydrogen as an additive to the main fuel	Formation of service centers on the basis of hydrogen fuel producers and power facilities

Selected on the basis of IMA priority strategic and operational objectives in the short- and long-term periods determine the development directions of the hydrogen energy, in particular the hydrogen fuel production technologies. To select the hydrogen production technology that would fully satisfy the hydrogen energy priority development directions the expert analysis was applied.

The results of the expert analysis reveal the advantage of compliance of the method of electrochemical water decomposition using energy in times of electricity consumption recession with the strategic and operational objectives. At the moment the technology of hydrogen production by the electrolysis of aqueous electrolyte solution is considered to be of little use for large-scale hydrogen fuel production due to great cost of electricity and electrolytic facilities. Nevertheless, the use of electrolysis for the production of hydrogen fuel is justified for the following reasons:

- high purity of the produced hydrogen (no complement cleaning is need before using);
- available resource base (in a practically unlimited scale);
- possibility of using reserve power plants in time of recession of electricity consumption to produce hydrogen fuel;
- obtaining valuable by-products (oxygen);
- versatility of using the energy source (nuclear, hydroelectric power stations and solar towers, etc...);
- modular electrolytic facilities.

TABLE IV
EXPERT ANALYSIS OF THE HYDROGEN PRODUCTION TECHNOLOGIES CONFORMITY WITH THE STRATEGIC OBJECTIVES

Methods	Strategic objectives			Σ
	Market (YC)	Technologies (XC)	Product (YC)	
	Reducing the cost of producing a liter of hydrogen fuel to the level of fossil analogues	Reducing the hydrogen fuel production energy intensity	Developing service infrastructure of hydrogen production facilities and hydrogen fuel vehicles	
Coal gasification	0,5	0,8	0,7	2
Steam conversion of methane	0,7	0,5	0,6	1,8
Fractional liquefaction of coke oven gas	0,6	0,6	0,5	1,7
Electrochemical water decomposition using the capacities in times of electricity consumption recession	0,7	0,8	0,8	2,3

TABLE V
EXPERT ANALYSIS OF THE HYDROGEN PRODUCTION TECHNOLOGIES CONFORMITY WITH THE OPERATIONAL OBJECTIVES

Methods	Operational objectives			Σ
	Market (YO)	Technologies (XO)	Product (YO)	
	Introduction of hydrogen as an additive to fossil fuel to increase its demand	Adaptation of the present nanomaterials for use in the hydrogen fuel storage and production systems	Application of composite materials, alloy steels in the hydrogen production, storage and use systems; minimization of moving parts, improving the heat balance	
Coal gasification	0,4	0,3	0,6	1,3
Steam conversion of methane	0,7	0,6	0,6	1,9
Fractional liquefaction of coke oven gas	0,5	0,5	0,7	1,7
Electrochemical water decomposition using the capacities in times of electricity consumption recession	0,8	0,7	0,8	2,3

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One of the main problems of the hydrogen energy development, associated with high hydrogen production energy consumption, can be partially solved with producing the hydrogen fuel by electrochemical water decomposition in times of downturn in the power system load due to the low cost price of electricity. To reduce the dependence of hydrogen production from the daily power system load requires measures to reduce the electrolysis energy intensity. With this purpose, there is development of catalysts and materials of electrodes to reduce the power consumption and the cost of the electrolytic facilities. In this area there have recently been two significant events:

– MIT's development of the catalyst system based on nickel and boron, replacing the platinum components and reducing the specific energy consumption for hydrogen production by 20 % [6];

– creation of the catalytic cell at the Swiss Federal Polytechnic University of Lausanne without using of ionic decrease membrane.

These advantages of the electrolytic hydrogen production technology in conjunction with the integral-matrix analysis allow us to consider different criteria in the following areas: product, technology, market, which creates a greater objectivity in investment decision-making:

– post-carbon energy development will largely contribute to solving the global environmental problems;

– to accelerate the hydrogen energy development it is necessary to create a competitive innovative fuel infrastructure based on the technologies that meet the competitive market criteria;

– the applied multi-criteria integral-matrix analysis makes it possible to justify electrolysis as a hybrid technology of reloading of the free-existing generating capacities and to achieve effective combined production of electricity and hydrogen fuel.

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