Methodological Approach to an Integrated Assessment of Systems for Remote Renewable Energy Supply

O.A. Baldynov[1,*], S.P. Popov[1]

[1] Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The use of renewable energy sources to reduce greenhouse gas emissions has become a global trend. According to forecasts of various international energy research organizations, this trend will persist in the future. As resources located near consumption centers are developed, the long-distance renewable energy transportation from areas where renewable sources operate with greater efficiency becomes a more pressing issue. Thus, the objective to establish an energy system using remote renewable sources arises. The study aims to elaborate a methodological approach for an integrated assessment of systems for energy supply from remote renewable energy sources. A distinctive feature of the proposed approach is a separate analysis of the main technological processes of production, conversion, storage, and use of energy carriers, with specific attention given to the generation of electricity from renewable energy sources. The Technique for order of preference by similarity to ideal solution (TOPSIS) is used for multi-criteria analysis of various solutions. This study aims to compare different energy systems for a project designed to export renewable energy from Russia (Sakhalin Island) to Japan (Yamagata Prefecture).**

***Index Terms* — remote renewable energy sources, electric hydrogen system, liquid hydrogen, methylcyclohexane, electrofuel, TOPSIS.**

I. INTRODUCTION

The increase in the level of global energy consumption, the decrease in the specific cost of wind turbines and photovoltaic modules, as well as international and national programs aiming to reduce greenhouse gas emissions have led to a surge in the share of renewable energy sources (RES) in global final energy consumption. According to forecasts made by energy research organizations and consulting agencies, this trend will persist in the future [1–3]. As resources located near consumption centers are developed, long-distance renewable energy transportation (above 1 000 km) from areas where renewable sources operate with greater efficiency (coastal wind zones, solar radiation in deserts) will be increasingly in demand. However, long-distance renewable energy transportation is costly and technologically challenging due to a low value of the capacity factor of wind farms and solar power plants, and their intermittent generation. Thus, the construction of long power transmission lines (PTL) for the renewable energy transportation is economically unviable due to the high cost of PTL and the low value of the capacity factor of solar and wind power plants.

The “Power to X (P2X)” concept can serve as a potential technological solution for developing SYstems for Remote Renewable Energy Supply (SYRRES). This concept

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[*] Corresponding author.
E-mail: oabaldynov@isem.irk.ru

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involves the production of hydrogen by electrolysis based on the electricity generated from RES. The hydrogen derived is then used as an energy carrier or transformed into other types of electrofuels (e-fuels) or liquid organic hydrogen carriers (LOHC). The use of “P2X” allows accumulation, seasonal storage, and long-distance transportation of renewable energy, which makes it possible to establish SYRRES.

Many countries, including Russia, plan to develop such systems. In 2020–2021, the Russian government approved several policy documents aimed at creating RES parks and advancing hydrogen energy industry to reduce greenhouse gas emissions and participate in international energy cooperation with other countries as an exporter of low-carbon energy sources [4–6]. The initial stage suggests producing hydrogen by steam-gas reforming of natural gas and water electrolysis using electricity generated by nuclear and hydropower plants. In the long term, it is planned to switch to the use of solar and wind power plants.

The “PtX” concept encompasses numerous technological paths to establishing SYRRES based on the production of hydrogen or other e-fuels and LOHC. These systems differ significantly from each other in the production process, numerical values of energy and economic efficiency indices, as well as the level of anthropogenic impact on the environment. Thus, the development of a methodological approach for an integrated assessment of systems for remote renewable energy supply becomes relevant, as this assessment will allow selecting their most reasonable option.

A wide range of studies explores the issue of establishing and comparing SYRRES. Let us consider general methodological approaches to assessing the effectiveness of such systems.

A comparative techno-economic (capital and annual operating costs) and environmental (CO_2 equivalent) assessment of energy transportation systems based on the use of gas pipelines, rail and road transport for the delivery of gaseous and liquid hydrogen, liquefied ammonia, and methane-hydrogen mixture (over a distance of 100 to 3 000 km for road transport and of 1 000 to 3 000 km for gas pipelines and rail transport) is presented in [7]. The study, however, does not explore the sea transportation of energy carriers and hydrogen-containing substances, despite the cost-effectiveness of this method of transportation.

A methodology developed for assessing projects aimed at using RES in local energy systems is presented in [8]. The use of RES is grounded in resource, economic, social, non-energy, budgetary, environmental, and energy significance. However, the paper does not consider alternative options for constructing energy systems based on converting electricity generated from RES into other energy carriers.

A comparative analysis of energy supply chains using liquid hydrogen, methylcyclohexane, and ammonia is conducted based on the calculation of energy losses and the cost of hydrogen for end consumers [9]. Energy carriers are produced using a carbon-free method and delivered to end consumers. However, the work does not consider the processes of intermediate storage and final consumption. A comparison of the reduced cost of long-distance sea transportation for energy carriers produced from RES was carried out in [10, 11]. Determining a reasonable route for exporting hydrogen and hydrogen-containing substances from Australia involves calculation of the transportation and intermediate storage cost, excluding the cost of energy carrier production. The technical and economic model developed by the authors is aimed at determining the final cost of 1 kg of liquid hydrogen (in the form of LH_2), liquefied natural gas (LNG), methanol, ammonia, and methylcyclohexane (MCH). The results indicate that ammonia ($0.56/kg H_2) and methanol ($0.68/kg H_2) are the least expensive hydrogen derivatives for transportation, followed by LNG ($1.07/kg H_2), MCH ($1.37/kg H_2), and liquid hydrogen ($2.09/kg H_2).

In [11], the authors compare capital costs of building hydrogen storage systems with a capacity of 500 tons/day of hydrogen in gaseous and liquid form, as well as the costs of producing LOHC and other energy carriers. The findings indicate that building an energy supply system based on the use of liquid hydrogen is more than twice as expensive as storing gaseous hydrogen and four times more expensive than energy supply using LOHC. Using ammonia and methanol as hydrogen carriers is a viable option for large-scale production due to the possibility of using existing infrastructure. However, their synthesis and dehydration are more energy-intensive and capital-intensive compared to LOHC.

The analysis performed in [12] examines the present value of the production of liquid organic hydrogen carrier (LOHC), specifically methylcyclohexane (MCH), along with liquid hydrogen and ammonia, utilizing hydrogen generated by electrolysis powered by renewable electricity in South Africa. This analysis spans the period from 2020 to 2050. In South Africa, the cost of renewable electrolytic hydrogen production is the lowest. Its production is based on electricity generated by a hybrid park of wind and single-axis photovoltaic power plants using a large-scale alkaline electrolyzer. The produced energy carriers and LOHC are transported to Japan and the European Union.

The existing methodological approaches fail to provide a comprehensive, systems study of the SYRRES. Most of the presented works limit the scope of the study, considering individual components or a set of components that constitute these systems. The criteria used to compare such systems are rather limited. In the studies discussed, the comparison of energy supply systems focuses primarily on the analysis of energy and economic efficiency. To determine a reasonable avenue to establish SYRRES, it is necessary to expand the set of criteria. The need for a multi-criteria assessment when comparing these systems is confirmed by the practice of formulating strategies for the development of hydrogen energy in various countries, in particular when considering options for process chains of importing RES energy from abroad. When comparing options for import chains, the Japanese government emphasized the importance of not only minimizing the cost of delivered energy resources generated from RES but also reducing the anthropogenic impact on the environment throughout their production and use.

II. Techno-Economic Model of the Energy Supply System from Remote RES

Previously, we developed a methodological approach for the Integrated Assessment of systems for transporting energy from remote renewable energy sources and presented it in [13]. This approach does not involve calculating the volume of energy services rendered to end consumers from the volume of e-fuels and LOHC delivered over the period. Energy services represent the volume of thermal electric energy production, as well as the productivity of vehicles. Calculation of this indicator allows assessing the efficiency of the systems in question for end consumers. For example, the delivered volume of LOHC can be comparable to or exceed the volume of liquid hydrogen delivered. After transporting LOHC, however, hydrogen needs to be extracted (dehydrogenated) from the chemical structure of LOHC, which is an energy-intensive process consuming part of the delivered energy. As a result, the volume of delivered RES energy and, hence, the volume of energy services rendered will decrease.

The approach published in [13] is also aimed at calculating the economic, energy, and environmental performance indicators for each option of energy transportation systems. However, it does not allow identifying the most reasonable option among the alternatives considered.

The aim of this study is to develop a methodological approach for the Integrated assessment of systems for remote renewable energy supply (SYRRES). The scientific novelty of this work is its contribution to addressing the previously identified gaps in the methodology [13].

In comparison with the study [13], the Integrated assessment of SYRRES has an expanded range of systems under consideration. In addition to systems based on the P2X concept: production of LOHC (methylcyclohexane, MCH), liquid hydrogen (LH_2), synthetic methane (SNG), and ammonia (NH_3), it analyzes an electric hydrogen (EH_2) system. Within the EH_2 system, the electricity generated from RES is transmitted via a high-voltage direct current (HVDC) transmission line and then is used to produce compressed hydrogen. Compressed hydrogen is then sold to consumers or recovered into electricity by reversible fuel cells (rSOEC) or a hydrogen combined-cycle gas turbine (CCGT) (Fig. 1).

As in the other power systems at issue, compressed hydrogen is produced based on RES. Compressed hydrogen storage is supposed to be on the consumer side, which eliminates the need to transport hydrogen. Electricity transmission via HVDC from the RES location to the hydrogen production site is described by the power transmission loss, the cost of power transmission line, and the limitation of its transfer capability.

In contrast to the methodological approach presented in [13], this work introduces the following changes in the integrated assessment of SYRRES.

To calculate the volume of energy services provided, the calculation of additional indicators was added to the techno-economic model of power systems. These are:

$$X = \frac{D}{\alpha^{CCGT/rSOEC}} \eta^{CCGT/rSOEC} \qquad (1)$$

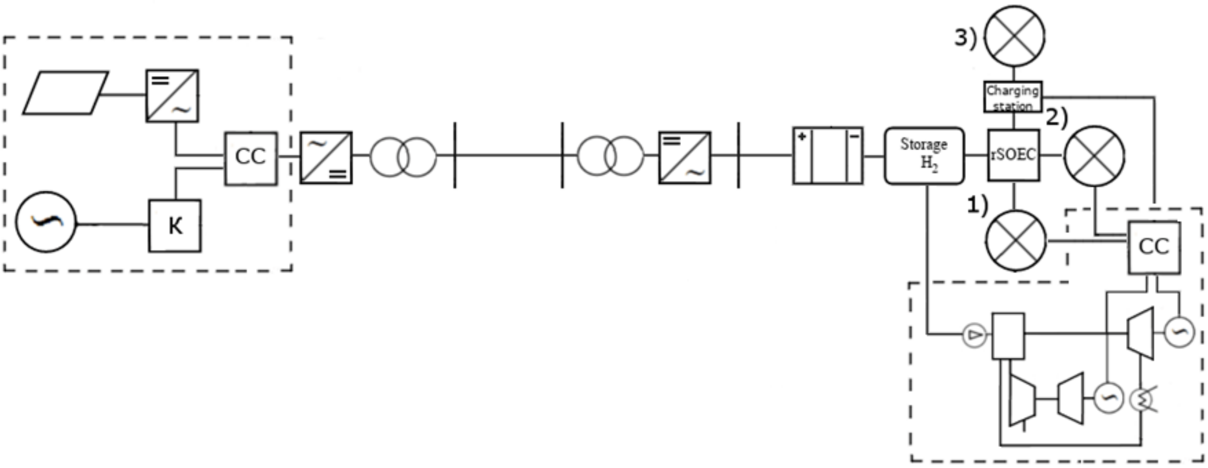

Fig. 1. Electric hydrogen system (1 – industrial consumers, 2 – consumers in the public sector, 3 – consumers in the transport

$$L_v = \frac{D}{\alpha^{BEV/FCEV/NG\ ICEV}} \tag{2}$$

where

D – volume of e-fuels / LOHC delivered to the consumer during the period, tons;

X – volume of energy services rendered to the consumer from delivered energy carriers during the period, MWh/year;

$\alpha^{CCGT/rSOEC}$ – specific electricity generation from CCGT or rSOEC, per ton of fuel;

$\eta^{CCGT/rSOEC}$ – efficiency of CCGT or rSOEC;

L_v – vehicle productivity, passenger-km;

$\alpha^{BEV/FCEV/NG\ ICEV}$ – specific consumption of electricity or fuel (hydrogen or SNG) Battery electric vehicle (BEV) / Fuel cell vehicle (FCEV) / Natural gas internal combustion engine vehicle (NG ICEV) (see Table 1 [14, 15]).

The reasonable way of constructing the system of energy supply from remote RES was determined using the “Technique for order of preference by similarity to ideal solution (TOPSIS)” [16, 17]. The TOPSIS is based on the idea that the selected alternative should have the shortest geometric distance from the positive ideal solution and the largest geometric distance from the negative ideal solution. As part of the Integrated assessment, the TOPSIS was revised to determine the most reasonable way of establishing SYRRES and now it consists of the following successive stages:

1) ranking the weight of criteria within the Integrated assessment of SYRRES depending on the degree of importance for the SYRRES project;

2) building a normalized matrix consisting of i alternatives and j criteria of the integrated assessment and constructing a normalized matrix:

$$S_{ij} = \frac{z_{ij}}{\sqrt{\sum_i z_{ij}^2}}\ , \tag{3}$$

where z_{ij} is alternative i assessed according to criterion j;

3) calculating the weighted normalized matrix:

$$m_{ij} = s_{ij} n_j\ ; \tag{4}$$

4) identifying “ideal” and “negative” solutions for each criterion:

$$\begin{aligned} m_j^+ &= \left((\max\ m \mid i \in I), (\min\ m \mid j \in J)\right), \\ m_j^- &= \left((\min\ m \mid i \in I), (\max\ m \mid j \in J)\right); \end{aligned} \tag{5}$$

5) calculating the distance for alternatives to “ideal” and “negative” solutions:

$$\begin{aligned} C^+ &= \sqrt{\sum_j (m_{ij} - m_j^+)^2} \\ C^- &= \sqrt{\sum_j (m_{ij} - m_j^-)^2} \end{aligned}\ ; \tag{6}$$

6) calculating relative proximity of the considered systems S_i to the ideal solution. The option closest to the

TABLE 1. Energy Consumption of a Vehicle for Different Fuel Systems

Vehicle type	BEV	FCEV	NG ICEV
Fuel consumption, kg/pass.-km	–	0.34	2.47
Electricity consumption, kW/pass.-km	0.56	–	–

"ideal" solution is recognized as the most reasonable way to establish SYRRES:

$$S_i = \frac{C_i^-}{C_i^- + C_i^+}\,. \tag{7}$$

III. Testing of the Integrated Assessment of a SYRRES within the Framework of the "Green Energy" Export from Russia to Japan

A production cluster on Sakhalin Island was one of the projects proposed by the Ministry of Industry and Trade of the Russian Federation for the production of hydrogen based on RES 18]. According to published data, it is planned to build a wind farm with an installed capacity of 200 MW alongside the establishment of infrastructure for the production and transportation of hydrogen in 2025. It is assumed that the hydrogen produced through electrolysis will be liquefied and transported to countries in the Asia-Pacific region [18]. The project does not indicate the locations of the wind farm, hydrogen production facilities, and hydrogen delivery points.

The production of liquid hydrogen is characterized by significant energy losses during storage and transportation. Based on the methodological approach for the Integrated assessment, a system based on the production of liquid hydrogen was compared with other SYRRES options. Within the framework of this study, the point of departure for e-fuels and LOHC is Uglegorsk port and the end point is Sakata port (Yamagata Prefecture, Japan). Let us consider the following SYRRES options:

1. **An electric hydrogen system**. A high-voltage direct current power transmission line with a total voltage of 720 kW and a length of 1 120 km will connect the wind farm near the port of Uglegorsk and the port of Sakata, where the production facility and compressed hydrogen storage facility are located;
2. **An energy system based on the production of liquid hydrogen (LH$_2$)**. Liquid hydrogen is produced in the port of Uglegorsk, and then transported by sea hydrogen tankers to the port of Sakata.
3. **An energy system based on the LOHC (MCH) production**. MCH is produced from hydrogen derived by the method of electrochemical splitting of water at Uglegorsk port. MCH is then transported by oil tankers to Sakata port.
4. **An energy system based on SNG production**. SNG is generated at Uglegorsk port utilizing hydrogen produced by the method of electrochemical water splitting. Then SNG is transported by gas tankers to Sakata port.
5. **An energy system based on ammonia (NH$_3$) production**. Ammonia is produced from hydrogen derived by the method of water electrolysis at Uglegorsk port. Then NH$_3$ is transported by ammonia sea tankers to Sakata port.

The length of the sea route between the ports of Uglegorsk and Sakata, when transporting e-fuels and LOHC by sea tankers (carrying capacity of 40 000 m3), is 1 240 km.

The methodological approach described in [13, 19] was applied to calculate the annual volume of e-fuels and LOHC exported from Russia to Japan, along with associated levelized cost as part of the first stage of the Integrated assessment. In this case, the cost of generating plants and distribution infrastructure (electric power plants, gas stations, storage facilities) is not considered due to their location on the territory of the importing country (Table 2).

Formulas (1) and (2) were used to calculate the volume of electric and thermal energy for CCGT and rSOEC (Fig. 2), as well as the performance of electrified vehicles for various combinations of their refueling and/or charging (Fig. 3). This indicator for BEV was calculated for various methods of electricity generation.

TABLE 2. Delivered Volume of E-Fuels/LOHC

SYRRES	Volume of delivered e-fuels/LOHC, tons	Levelized cost of e-fuels/LOHC, USD/kg
LH$_2$	9 600	14.7
MCH	5 600	14.4
SNG	8 700	13.9
NH$_3$	8 500	13.7
EH$_2$	9 100	13.9

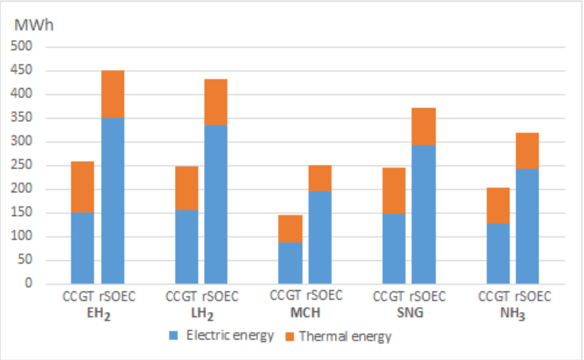

Fig. 2. Thermal and electric energy production

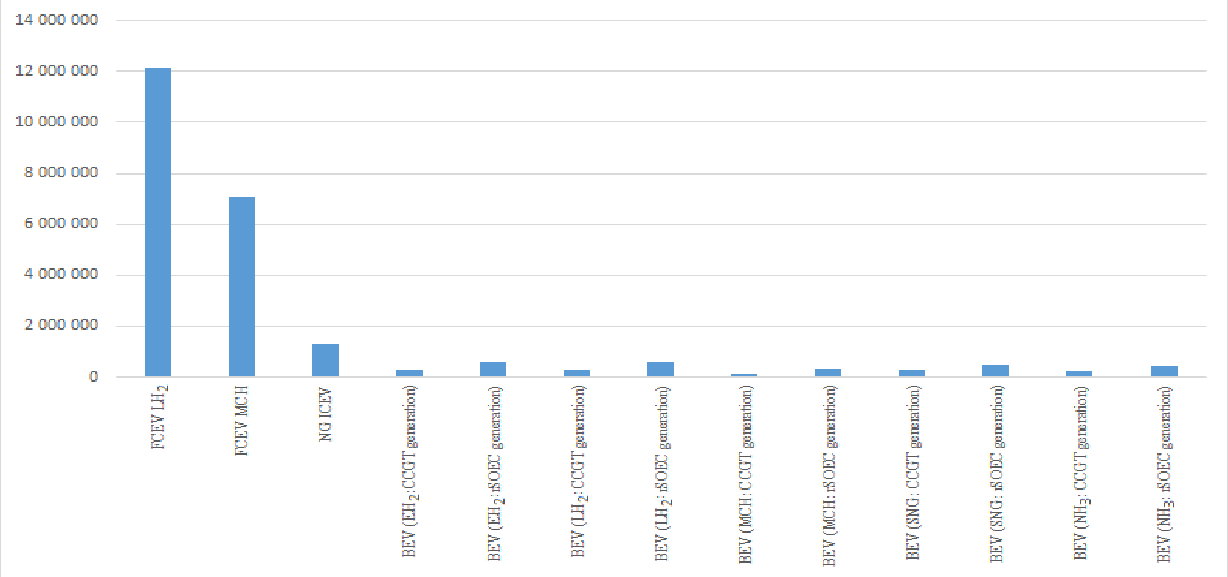

Fig. 3. Vehicle productivity, passenger-kilometer.

TABLE 3. Integrated Assessment of SYRRES

Criteria	Units	EH_2	LH_2	MCH	NH_3	SNG
Technical:						
Energy losses	%	41.7	48.9	69.1	64.5	60.1
EROEI	–	2.05	2.1	1.85	1.72	1.67
Economic:						
Levelized cost	USD	14.7	14.4	13.9	13.7	13.9
NPV	bn USD	1.326	1.314	1.271	1.352	1.337
Environmental:						
CO_{2e}	t	140.3	149.8	267	296.1	294.7
Geopolitical factor						
Possibility of replacing an importing country	–	0.5	1	1	1	1

The second stage of the Integrated assessment focuses on calculating the numerical values of the criteria (Table 3). The establishment of systems for energy supply from remote RES also involved assessing geopolitical factors. The history of the Asian Super Grid project illustrates Japan's high interest in ensuring energy security when developing international power transmission lines that would connect the country with other participants in the global electric power system [21–23]. At the same time, the country widely used liquefied natural gas (LNG), supplied by sea LNG tankers from various exporters.

If Japan declines to import energy from Russia, the export of e-fuels and LOHC will be redirected to other Asia-Pacific countries. In this case, sea transportation of e-fuels and LOHC is preferable in terms of political risks, as it facilitates consumer diversification. Thus, the SYRRES options were ranked as follows: in the case of impossibility of changing the direction of e-fuels and LOHC transportation – 0.5, in the case of SYRRES independence from consumers – 1.

The third stage of the Integrated assessment employed the TOPSIS to determine the most reasonable option for establishing SYRRES. The considered hydrogen production project on Sakhalin Island is an export-oriented project aimed at generating profit. In this regard, at the first step of TOPSIS, the emphasis was placed on assigning

TABLE 4. Weights of Criteria in the Integrated Assessment of SYRRES

Energy losses	EROEI	Levelized cost	NPV	CO_2e	Geopolitical factor
0.15	0.15	0.2	0.2	0.15	0.15

TABLE 5. Normalized Matrix

Criteria	Energy losses	EROEI	Levelized Cost	NPV	CO_2	Geo-political factor
EH_2	0.323	0.486	0.465	0.445	0.261	0.243
LH_2	0.379	0.498	0.456	0.449	0.279	0.485
MCH	0.535	0.439	0.440	0.431	0.498	0.485
NH_3	0.499	0.408	0.434	0.458	0.552	0.485
SNG	0.465	0.396	0.440	0.453	0.549	0.485

TABLE 6. Weighted Normalized Matrix

Criteria	Energy losses	EROEI	Levelized Cost	NPV	CO_2	Geo-political factor
EH_2	0.048	0.073	0.093	0.089	0.052	0.049
LH_2	0.057	0.075	0.091	0.090	0.056	0.097
MCH	0.080	0.066	0.088	0.086	0.100	0.097
NH_3	0.075	0.061	0.087	0.092	0.110	0.097
CM	0.070	0.059	0.088	0.091	0.110	0.097
SNG	0.048	0.073	0.093	0.089	0.052	0.049

weights to the criteria based on economic efficiency, as detailed in Table 4:

In the second step of TOPSIS, the obtained numerical values of the Integrated assessment criteria were employed to calculate the normalized matrix elements using formula (2) (Table 5).

The third step involved calculating the values of the weighted normalized matrix elements using formula (4) (Table 6).

At the fourth step, “ideal” and “negative” solutions were identified when choosing SYRRES options (Table 7).

At the fifth step, the distance for alternatives to both the “ideal” and “negative” solutions was calculated (Table 8).

The sixth step of the TOPSIS involved calculating the distance of relative proximity to the ideal solution for each system at issue. The results of calculations based on TOPSIS within the framework of the Integrated assessment show that the reasonable SYRRES option under the accepted assumptions is a system based on the production of liquid hydrogen (Fig. 4).

TABLE 7. “Ideal” and “Negative” Solutions

m_j^+	0.048	0.075	0.087	0.092	0.052	0.097
m_j^-	0.080	0.059	0.093	0.086	0.110	0.049

TABLE 8. Calculated Distance for Alternatives to the “Ideal” and “Negative” Solutions

Criteria	C^+	C^-
EH_2	0.04902	0.06765
LH_2	0.01026	0.07828
MCH	0.05791	0.05037
NH_3	0.06524	0.04955
SNG	0.06329	0.05008

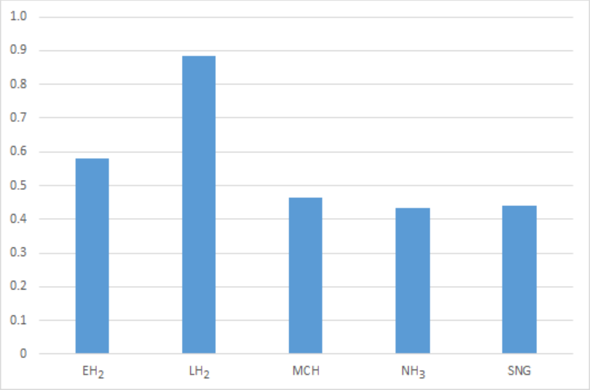

Fig. 4. Determining a reasonable energy system using TOPSIS.

IV. ANALYSIS OF THE OUTCOMES ACHIEVED

The results of the Integrated assessment confirm the SYRRES option based on the production of liquid hydrogen within the framework of the hydrogen production project on Sakhalin Island. This system is characterized by high values of economic indices in comparison with systems based on the production of MCH, ammonia, and SNG. Energy losses of the electric hydrogen system are minimal; however, Japan’s decision to stop importing energy resources from Russia will make these HVDC power lines unnecessary and lead to their shutdown.

V. CONCLUSIONS

This paper presents a methodological approach to the Integrated assessment of systems for remote renewable energy supply. The study examines an electric hydrogen system utilizing a HVDC power line for the transmission of electrical energy and a hydrogen subsystem for its storage. The TOPSIS is adopted to determine a reasonable SYRRES option.

Based on the proposed methodological approach, the Integrated assessment of the energy systems was performed for the case study of exporting Russian energy resources to Japan. The results obtained demonstrate the viability of this approach and reveal its potential for conducting pre-project studies of the development of systems for remote renewable supply.

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Oleg Baldynov gained the Bachelor's degree in Finance in 2015 and Master's Degree in Innovation Management in 2017 from Irkutsk National Research Technical University, Russia. In 2017–2021, he was a Ph.D. student at Melentiev Energy Systems Institute (ESI) SB RAS. His research interests include renewable energy sources, hydrogen energy, and energy transmission.

Sergei Popov is a Senior Researcher at the ESI SB RAS. He is responsible for the analysis of the East Asian and Asia-Pacific energy markets. He joined the ESI SB RAS in 1982 and received the Ph.D. degree in Modeling Energy Systems from the ESI SB RAS in 1993. In 2004–2011, he worked in the Asia Pacific Energy Research Center, Japan. His research interests include energy modeling, energy policy development, and international energy cooperation issues.