Evaluation of energy efficiency of the long distance energy transport systems for renewable energy

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Abstract This article describes the systems of long-distance transport of energy from renewable energy sources. A comparative analysis of the energy efficiency of energy complexes in the transport of energy analysis is performed carriers such as electricity and hydrogen in a liquefied and chemically bound state.

Key words: renewable energy, efficiency of energy complexes, energy transport, hydrogen energy, direct current lines,

1 Introduction

According to energy forecasts, the share of primary energy consumption from renewable sources will significantly increase in the future [1]. The potential for the use of renewable energy sources (RES) increases under certain climatic conditions allowing to raise the efficiency of production of energy: strong winds at the sea shores of The Arctic and Pacific oceans, the solar radiation - in the arid areas of Australia and East Asia.

Centers of energy consumption can be located at a considerable distance from the territories where renewable energy can be produced with greater efficiency. As a result import of renewable energy may become possible; this raises the question of organizing its long-distance transport.

Solar photovoltaic (SPP) and wind stations (WPP) are the most widely spread among renewable energy generators, those technologies for the production of electricity have been successfully commercialized in recent years. The organization of energy transport infrastructure requires significant investment and depends on many factors: the achievements of scientific and technical progress in the field of materials science and equipment, industry capacities, the availability of the necessary manpower. However, today there are projects of the energy transmission over 1,000 km distance (see Table 1) [2-9].

Table 1 Long-distance energy transport projects

Country	Project	Distance, km	Commis-sioning
Brazil	Rio Madeira HVDC Classic - from hydropower plants in the north-west of Brazil to São Paulo (± 600 kV)	2 375	2014
China	HVDC from Xinjiang Uygur Autonomous Region to Anhui Province (± 1100 kV)	3 293	2019
Egypt, Cyprus, Greece	EuroAfrica Interconnector DC underwater energy network connecting Egypt and Greece currently being designed.	1 707	2021
Israel, Cyprus, Greece	EuroAsia Interconnector – DC underwater energy network connecting Israel and Cyprus and then Greece currently being designed.	1 518	2023
Brazil	An ethanol pipeline connecting ethanol plants in the state of Mato Grosso and Rio de Zeneiro currently being designed.	2 000	no data
Japan	Hydrogen Spera – a project on the marine transport of hydrogen-containing substances (methylcyclohexane), which will ensure the supply of hydrogen from Australia to Japan.	7 000	2020

Various options for the transport of energy from renewable energy sources are presented in these projects and the question that arises is of the comparative energy efficiency of such systems and their competitive advantages. Let us consider the means for long distance transportation systems to deliver renewable energy to consumers.

2 A review of transport technologies

The transportation of electricity from renewable energy sources to consumers is based on the construction of high-voltage direct current lines (HVDC). This technology ensures the transmission of electrical energy over long distances with minimal losses. An alternative method of transportation of energy from RES is based on the concept of synthetic fuel production «Power to Gas» (P2G). The starting point for P2G is the use of excessive electrical energy to produce hydrogen as an energy carrier. At the first stage, electricity being generated by RES is consumed by electrolyzers that produce hydrogen. Further, there are several possible technologies available:

- transport and direct use of hydrogen as an energy carrier,
- production of liquid organic hydrogen carriers (LOHC) with their subsequent transport and dehydrogenation (release) of hydrogen at consumer side,
- production of other energy carriers based on hydrogen, like synthetic methane, ammonia, etc.

Hydrogen can be transported in the gaseous or liquefied state by traditional means of transport - by road, rail, sea, as well as through pipelines. The physic-chemical properties of hydrogen present challenging technical requirements for the systems of its use, storage and transport hydrogen. In this regard, the construction of the trunk hydrogen pipelines is inefficient, since expensive materials are required for the internal anti-corrosion coating. The transport of hydrogen through the pipeline costs 1,5 more than the transport of natural gas [10].

There are two ways to reduce the impact of hydrogen on the elements of storage and transport systems:

1) the use of a gas mixture of natural gas and hydrogen. Hydrogen blending of 5-15% is allowed for pipeline transportation [11]. The ratio of gases may vary depending on the material of the pipeline and gas equipment. The risks are minor with technological control in place and compliance with the permissible content of hydrogen both for the network of pipelines, and for end users. The use of a gas mixture can be considered as a method of gradual transition to hydrogen energy.

2) the use of substances-carriers that contain hydrogen in the chemical composition. Such substances came to be known as Liquid Organic Hydrogen Carrier (LOHC).

LOHC includes, in particular, methylcyclohexane (MCH), an organic substance obtained through the hydrogenation of toluene. Hydrogen in the MCH composition can be safely stored and transported in a liquid state at ambient temperature and pressure.

Hydrogenation of toluene (the process produce MCH) and the reverse process of hydrogen product occur without the consumption of toluene. After dehydration on the consumer’s side, toluene is transported back to recycle the production of MCH. The process of methylcyclohexane dehydrogenation is endothermic and occurs at high energy costs that reduce the efficiency of the whole chain. Chiyoda Corporation was able to increase the efficiency of the MCH production process to 99% and the dehydrogenation process to 98% during the demonstration tests in 2018 [12].

In accordance with the UN Recommendations on the transport of dangerous goods, methylcyclohexane is classified as a highly flammable liquid, its hazard category is the same as that of gasoline and diesel, MCH belongs to the 3rd hazard class of chemicals (Low Hazard Substances) [14]. The use of MCH has a high technological capacity for the storage and transport of hydrogen over long distances, its use allows to exclude the damaging effect of hydrogen on metals. MCH practically doesn't evaporate.

The existing petroleum infrastructure can be used for the MCH. In the case of large volumes of transport of hydrogen, the most suitable way of delivery for both hydrogen and MCH will be tanker transportation. Transmission of the MCH requires two branches: direct - for the transfer of MCH and the reverse - for the transfer of toluene [11].

Ammonia is also classified as LOHC. Ammonia contains in its composition more hydrogen on the volumetric weight in contrast to the MCH. Moreover ammonia can be used in energy industry as a fuel at ammonia fuel cells and steam-gas station. However, during ammonia combustion hazardous emissions are generated.

Ammonia must be stored and transported under a pressure of 0.87 MPa that leads to additional energy losses [13]. A temperature of at least 400°C is demanded to dehydrate ammonia. The temperature of methylcyclohexane dehydrogenation is 3-4 times lower. Ammonia technologies are presented in Table 2. [13, 14, 15, 16].

Table 2 Comparative characteristics of methylcyclohexane and ammonia

Indicators	MCH	Ammonia
Hydrogenation temperature (°C)	200 – 400	350 – 900
Dehydration temperature (°C)	100 – 200	400 – 600
H_2 density (wt%)	6,16 %	17,8 %
Storage losses	< 0,14 % / year	0,14 % / year

Another option for the transport of renewable energy is production of synthetic methane (SM). Is allows to introduce the renewable energy into the existing gas system without any restrictions, and avoid intermittency and energy storage issues. The cost of SM is higher than the cost of natural gas, however, its use may be preferable to natural gas with a tax burden on greenhouse gases emission; where exists a necessity to reduce dependence on energy-exporting countries and a number of other similar conditions. While the process of SM production by reacting hydrogen with carbon dioxide under pressure is energy-intensive, with high energy losses, and therefore this method of energy transport is not considered in this paper.

3 A review of hydrogen consumption technologies

The use of hydrogen to satisfy energy services is possible for all groups of consumers: buildings, transport, and industry. In addition, with hydrogen produced it is possible to get not only electric power, but also heat energy. The efficiency of electricity generation on fuel cells ranges from 30% to 55%; the total efficiency can be increased through the use of heat energy (see Table 3). The high efficiency indicator of hydrogen is demonstrated by the project “Ene-farm” for small power consumers in Japan. A solid-oxide fuel cell (with a capacity of 200 to 700 W, depending on the model) ensures the production of electrical and heat energy, the efficiency of its combined cycle reaches 87 percent [18].

Table 3 Comparative characteristics of fuel cells

Fuel cell type	Operating temperature	Electric power generation efficiency	Combined cycle efficiency	Capacity
Proton-exchange membrane (PEMFC)	60 – 160°C	30 – 35%	50 – 70%	0,1 kW
Phosphoric acid (PAFC)	150 – 200°C	35%	70–80%	11 MW
Molten carbonate (MCFC)	600 – 700°C	45 – 50%	70 – 80%	3 – 60 MW
Solid oxide (SOFC)	800 – 1 000°C	45 – 60%	70 – 90%	1 – 100 MW

The use of fuel cells is also possible for major consumers. In particular, solid-state oxide fuel cells

Energy supply to consumers with the help of hydrogen can be realized not only through fuel cells. Mitsubishi Hitachi Power Systems is developing gas turbine and steam-gas systems. Currently, the company has created several gas turbine plants operating on a gas mixture (20% H_2 / 80% CH_4 and 30% H_2 / 70% CH_4); their use allows to reduce CO_2 emissions level and provides natural gas economy. The company's goal is to create pure hydrogen combine cycle turbine system with efficiency not less than 65 percent [20].

Energy Efficiency Review Assessment of energy efficiency of long-distance energy transport systems of renewable energy is carried out on the basis of a comparison of the elements of the transport system and the efficiency of use by end-consumers. The purpose of this paper is to compare the total losses of long-distance energy transport systems (over 1,000 km) from WPP and SES to the end consumer.

One of the most important quantitative indicators of energy efficiency is the amount of losses. For comparison of transmission systems the problem of energy transport in the amount of 10 million tons of fuel equivalent at a distance from 1,000 km to 7,000 km is considered. Three long-distance transport systems are considered: 800 kW HVDC power line, liquefied hydrogen and methylcyclohexane transport. Corresponding transport chains are shown in Fig. 1.

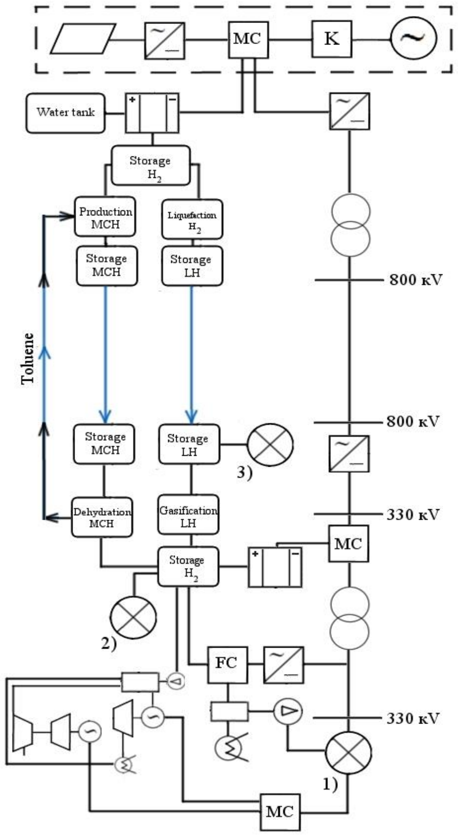

Fig. 1. Long distance energy transportation system

Let us consider an electric power facility based on the transport of energy through DC lines. The electricity generated by solar cells and/or wind generators is transmitted to the control center MC that carries out the switching of current to the HVDC terminal or to the electrolysis plant for the production of hydrogen. At the receiving terminal of the DC power lines, electricity is supplied to industrial consumers (1 at Fig. 2), for transport (2 and 3 at Fig. 2) and for buildings (2 at Fig. 2).

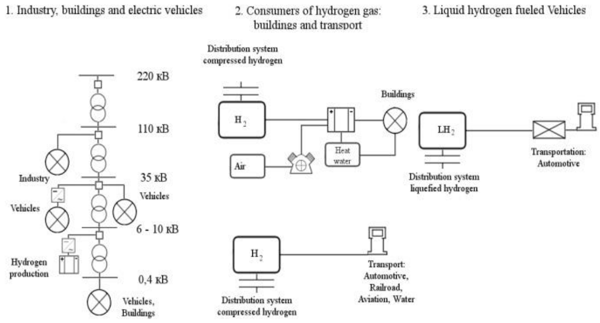

Fig. 2. Distribution network

The energy losses in case of electric power infrastructure is presented in Table 4. Data on losses in distribution lines, shown in Table 4, are average values for the Russian Federation. The level of losses in distribution lines and the efficiency of electrical equipment can differ significantly a particular country [23].

Table 4 Losses in equipment of the electric power facility

Object	Losses, percent	Object	Losses, percent
HVDC ±800 кВ	3 per 1 000 km	Inverter	2 – 3
Main lines	5 – 10	Monitoring center	0,95
Distribution network	7 – 10	Step-down transformer	2

Hydrogen models of RESs energy transportation. The electricity generated at the SPP and WPP is supplied to electrolysis stations for the production of gaseous hydrogen. The next step is the hydrogen's liquefaction at a temperature of -250°C. The energy intensity of this process in various researches ranges from 15% to 45% of the output hydrogen energy [10, 22]. Hydrogen liquefaction increases its density (from 0.09 kg/m^3 to 70 kg/m^3), thus the volume of hydrogen to be stored is significantly reduced. Special standards of control for liquefied hydrogen are required during its storage and transportation, which affects the final cost of fuel. Currently, only a few models for utilize liquefied hydrogen as a fuel for fuel cell vehicle. The remaining consumer groups use compressed hydrogen. Gasification becomes a necessary stage, and as a result of this process additional losses arise. Losses during storage and transportation, in contrast to power transmission lines, do not depend on distance, but on time: 0.02% - 0.03% per day for liquefied and 0.5 - 1% per day for gaseous hydrogen [17]. Calculating the efficiency, the time from the moment of production of hydrogen to its consumption must be taken into account. The storage time of hydrogen gas is taken from the conditions of safe use in 1 day. Transport losses are estimated based on the range of losses (see Table 5).

Table 5 Losses in marine transportation of liquefied hydrogen

Process	Losses, percent	Process	Losses, percent
Electrolyzer	10 – 20	Gasification of liquefied hydrogen	9
Hydrogen storage	0,5 – 1 (per day)	FC Electric power generation	40 – 60
Hydrogen liquefaction	15 – 45	FC Combined cycle	10 – 30
Storage of liquefied hydrogen	0,02 – 0,03 (per day)	Hydrogen combined cycle gas turbine	35

Hydrogen can be transported as part of methylcyclohexane. Losses during transport and storage of MCH are minimal; as a result, the storage of hydrogen in the MCH composition is less dependent on time (see Table 6).

Table 6 Losses in methylcyclohexane marine transport

Process	Losses, percent	Process	Losses, percent
Production ()	1 – 5 %	Toluene hydrogenation	30 %
Storage	< 0.14 % / year	Power generation (fuel cell)	40 – 60%
Transportation	< 0.14 % / year	MCH dehydration	2 – 30%

Conclusions Figure 3 shows a graph of the minimum energy losses of renewable energy HVDC lines, transport of liquefied hydrogen and MCH.

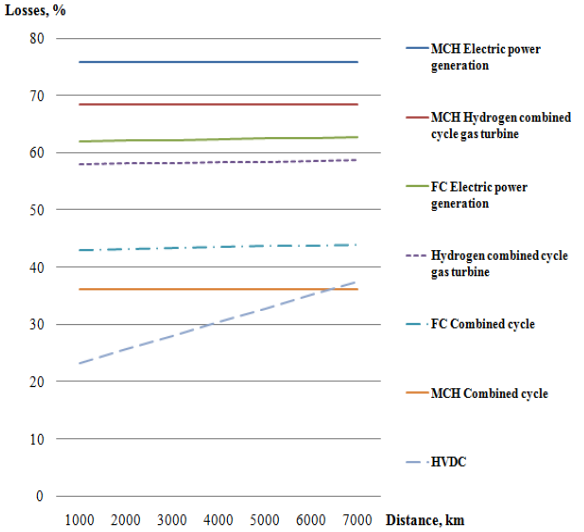

Fig.3 Evaluation of energy efficiency for the long distance NRE energy transportation modes

Minimal losses in energy transport are achieved with the use of direct current lines (from 23% to 37.5%). The maximum losses arise during transmission in distribution networks. In calculating the losses of electric power transport, restrictions on the maximum permissible load of the receiving network were not taken into account.

The most effective method of hydrogen transportation hydrogen is the use of methylcyclohexane. The total losses reach 36.2% after cogeneration fuel cells. In addition, due to the low level of losses and the wide temperature range, the MCH is suitable for long-term seasonal storage of electricity.

The total losses in the transport of liquefied hydrogen are higher than in the transport of MCH (from 43% to 44%). Significant energy losses of hydrogen occur during the transition from a gaseous state to a liquefied one. An established system of distribution and storage of hydrogen which is minimizing losses is essential. Otherwise, the losses of hydrogen during storage can significantly reduce the overall efficiency of the entire transport system.

As can be seen in fig. 3, losses in electric power transport are less than in the transport of hydrogen and MCH. The transport of renewable energy in the form of MCH becomes more energy-efficient than using transmission lines DC starting from a distance of 6,000 km. Currently, hydrogen technologies are in the stage of demonstration projects, probably the energy efficiency of hydrogen transport will be higher in the further development. As noted, the energy efficiency of RES with curtailments were not taken into account. In practice, this relates to additional losses in dispatching and transmission of electricity. The transport of hydrogen or MCH does not have such limitations, since the use of appropriate technologies implies long-term storage of energy carriers and consumption at the appropriate moment.

Energy efficiency is an important indicator in assessing transport systems; the choice of the optimal method should be based on multiple criteria. It is necessary to take into account technical, economic and environmental aspects. Depending on the distance and other factors, a combined energy transport system of RES can be a more efficient way: electric transport (via DC main lines) and storage on the consumer side in the form of MCH and subsequent dehydration. Such a system will be less dependent intermittent generation of renewable energy sources; will allow accumulating energy, reducing the requirements for carrying capacity of the main transmission lines DC. A comprehensive assessment of the long-range transport of energy from renewable energy sources should be further explored.

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