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Prospects of Transition of Air Transportation to Clean Fuels: Economic and Environmental Management Aspects

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Abstract – *The purpose of this paper is to forecast the economic and environmental performance of two promising fuel and energy technologies for aviation, which are at the prototyping stage (the use of electric energy and hydrogen fuel cells), in comparison with traditional fuel. The basic methodology of the study is life cycle assessment (LCA), defined by the family of international environmental management standards ISO 14000. The study revealed that from an environmental point of view, one of the most preferred technologies in the medium term is the use of hydrogen produced by steam reforming. In the long-term (with the entry of fully electrified aircraft into the market), technologies for using electricity as a fuel produced either by wind / solar generation or by gas generation of a combined cycle also demonstrate high environmental performance. Moreover, according to the most important for human health categories of environmental impact, it is preferable to generate electricity for fully electrified airplanes by combined gas generation cycle.*

Keywords – *aviation fuel, electric aircraft, environmental impact, hydrogen fuel, life cycle analysis.*

1. INTRODUCTION

In recent years the major aircraft-manufacturing corporations in the world have intensified research and development in the field of alternative fuels, mostly thanks to the state support measures in leading countries in the aerospace industry [1],[2]. Aviation biofuels (commonly mixed with traditional ones) are currently actively used in air transportation in several US states and successfully tested in other countries [2],[3]. Flight tests and revision of several prototypes of hydrogen-powered aircraft of various classes are ongoing (Rapid 200-FC, HY4, Element One, *etc.*) [4]. Some major projects for electrifying aircrafts are well known, such as Boeing's Subsonic Ultra Green Aircraft Research (SUGAR) project to create a hybrid aircraft (using both conventional fuel and electric power to batteries) and Bauhaus Luftfahrt's Ce-Liner project to create an all-electric airplane [5],[6].

The main reasons for the innovative activity in this area are the high risks associated with an increase of environmental issues as a result of the growth in global air traffic (the projected annual growth rate of passenger traffic is 4–4.4% before 2035) and the amount of hydrocarbon fuel consumed [2]. Another important factor is the fact that in recent decades, the technological development of aircraft industry has reached a saturated state: the process of improvement technical and economic characteristics of civil aircraft has almost stopped, which hinders the further increase in the availability of air transportation technology, as well as blocks the entry of new manufacturers into the aircraft industry [7]. In order to win this challenge, the development of new technological trends is required, the most promising of which is the elaboration of new, more affordable and environmentally friendly energy supplies for aircrafts [8].

The full range of consequences of the emerging adjustment to new fuel technologies in aviation is not fully understood, especially in terms of the transition to hydrogen fuel cells or electricity. Despite the growing body of literature on the topic of alternative fuel, there is still considerable uncertainty with regard to socio-economic, environmental and resource efficiency of new fuel technologies, considered for the full life cycle. Another question that needs to be raised is the possible impact of jet fuel change on the already established global fuel and energy infrastructure. It should be noted that for countries that are actively modernizing their energy infrastructure and are mastering new renewable energy technologies, such as Russia in recent years [9], it is very important to understand which direction to move in. Co-direction of the development of energy infrastructure and transport technologies can significantly reduce the burden on the environment and increase sustainability [10]. Therefore, studies aimed at assessing the environmental, energy and economic effects of new types of fuel technologies in air travel, taking into account not only the direct use of fuel during the operation of the aircraft, but also the earlier stages of the life cycle (hydrogen and electricity production and storage, battery production *etc.*) are important and have a lot of potential political applications.

This paper examines the economic and environmental efficiency of the full life cycle of two promising fuel technologies for aviation, which are both at the prototyping stage (electricity as a fuel and hydrogen fuel cells), in comparison with traditional fuel.

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2. LITERATURE REVIEW

The impact of air transport on society and the environment on a global scale is a popular research topic in both the scientific community and business intelligence of the air industry. Current papers on this issue can be divided into three main groups.

The papers of the first group focus on detailed analysis of the potential impact of the transition of aviation to various types of biofuels on the environment. This question is best studied in literature, some powerful models have been developed to simulate the full life cycle of biofuels, such as GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). Thus, the study of Argonne National Laboratory [11] gives a comparison of Fischer–Tropsch (FT) jet fuel from natural gas, coal, and biomass; bio-jet fuels from fast pyrolysis of biomass; and hydroprocessed renewable jet fuel from vegetable and algal oil on full well-to-wake (WTWa) type of life cycle using GREET model. The only analyzed parameter of environmental impact is air quality which is evaluated by the value of emitted sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter with sizes measuring 10 micrometers or less (PM10), volatile organic compounds (VOC), carbon monoxide (CO), and GHGs (CH_4, N_2O, and CO_2).

Trivedi *et al.* [12] considered the feedstock-to-fuel pathways for conventional jet fuel and several alternative fuels: FT jet fuel from natural gas, coal and/or switchgrass; hydroprocessed esters and fatty acids jet (HEFA-J) fuel from soybean, palm, rapeseed and jatropha; and advanced fermentation jet (AF-J) fuel from sugarcane, corn grain and switchgrass. The only analyzed metric is energy return on energy investment (EROEI).

In [13] the authors investigated the lifecycle GHG emissions of several types of biofuels derived from cultivated feedstock crops (oily, starchy, sugary, and lignocellulosic crops), as well as biofuels from agriculture and forestry residual, municipal solid waste and waste fats, oils and greases. The boundaries of production system include only life cycle of the fuel: feedstock production and transportation, fuel production and transportation, and combustion. A special feature of the study is that emissions are calculated not only based on existing data, but also forecast changes in LCA emissions on the time horizon until 2050.

Han *et al*. [14] examine well-to-wake (WTWa) life cycle of ethanol-to-jet from corn and corn stover, and sugar-to-jet from corn stover, each produced with two manufacturing options. The only GHGs emissions are analyzed.

Klein *et al.* [15] compare Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch Synthesis (FT), and Alcohol to Jet (ATJ) biofuels production pathways using several environmental metrics: GHGs emissions (climate change), human ecotoxicity, terrestrial acidification, land occupation and fossil depletion.

The second group of studies considers the focus of research on the environmental (and, in some cases, economic) effects of liquefied hydrogen, used as fuel for aircraft. As a rule, the environmental effects of hydrogen fuels are considered in comparison with conventional fuels or with biofuels. The number of compared parameters may be different.

Janic [16] estimates the medium-to long-term direct emissions of GHGs by the commercial air transportation under assumption that conventional fuel is completely substituted with biofuels (particularly, Fischer-Tropsch Synthetic Paraffinic Kerosene) or, as an alternative, with liquid hydrogen. The study considered only GHGs emitted from direct burning of all types of fuels.

Schönsteiner *et al*. [17] consider energy use and GHG emissions for conventional jet fuel, liquefied natural gas, biofuel from oil palm and liquid hydrogen (LH_2) produced by electrolysis process through well-to-tank (WTT) life cycle. The advantage of this study is that it takes into account the peculiarities of the local energy system, as well as the little-studied stages of the life cycle of liquefied hydrogen such as seasonal and short-term storage, transportation and distribution. Wulf *et al.* in [18] on the contrary, focus to the questions of hydrogen transportation and distribution, considering such environmental impact categories as climate change, acidification, ozone depletion, human toxicity, particulate matter, freshwater ecotoxicity, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, ionizing radiation – human health and ecosystems, photochemical ozone formation, and resource depletion, mineral, fossils and renewables.

Pereira *et al.* [19] compare WTWa of liquid natural gas (LNG) and liquid hydrogen (LH_2) produced by different technologies (steam reforming, electrolization with electricity from wind, photovoltaic (PV), hydro) with conventional jet fuel using MACV2H2_v2.0 model. Their analysis not only considers the energy consumption and CO_2 emissions, but also several pollutants, such as HC, CO, NOx and PM.

Bicer and Dincer [20] evaluate the overall life cycle of an aircraft running on conventional (kerosene) and 5 types of promising alternative fuels (ethanol, LNG, LH2, liquid ammonia, methanol). The environmental impact categories taken into account in this study are human toxicity, global warming, land use, depletion of abiotic resources and stratospheric ozone depletion. The strength of this study lies in the fact that the life cycle of air transportation is considered with the widest possible boundaries, including the production of the aircraft itself, as well as the construction, maintenance and disposal of the ground infrastructure (airport).

The third group of publications is devoted to the analysis of the environmental effects of fully electrified aircraft and is so far the smallest. Most of the publications of this group are presentations at conferences. Thus, Plötner *et al.* [21] compare conventional aircraft and electric aircraft – exemplified on Ce-Liner concept by GHGs emissions through the entire life cycle and declare that Ce-Liner should save at least 42% of GHGs emissions with an expected growth of renewables in worldwide electricity mix by 2035.

Schulz, on the contrary, claims that the battery powered aircraft does not save CO_2 [22]. His study is based on the ReCiPe life cycle assessment methodology and considers not a single environmental impact, but a whole range of ecology effects such as climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil fuel depletion. The results of these studies so far partially contradict each other, mainly due to the large share of uncertainty in the assessment of the environmental impacts for this future technology.

The recent paper of Gnadt *et al.* [23] can be noted as the most complete. The authors analyze direct and non-direct CO_2 emissions of all-electric aircraft on a flight-by-flight basis with conventional aircraft based on current U.S. electricity generation structure. The advantage of this study is that authors examine two scenarios of changes in the electricity system and its influence on environmental performance both for a conventional and an all-electric airplane. However, this study does not include the lifecycle emissions associated with battery manufacturing.

Thus, the authors have not identified any studies that directly compare the environmental effects of fully-electrified aircraft with hydrogen-powered aircraft.

3. METHODOLOGY

3.1 Life Cycle Assessment according to ISO 14040-14043 Standards

The basic methodology of the study is life cycle assessment (LCA), defined by the family of international environmental management standards ISO 14000. According to ISO 14040:2006, life cycle assessment (LCA) includes consideration of the entire product life cycle from the extraction of raw materials and production of energy needed for the manufacturing of a product to its use and the subsequent cessation thereof followed by recycling. For all transport systems (automotive, rail, air, sea, river), the structure of the life cycle is considerably complicated due to the emergence of a new independent branch. In addition to the life cycle of the vehicle itself, the analysis also takes into account the life cycle of the fuel for this vehicle.

If air transportation as a final product is considered, then the full life cycle in the case of conventional fuel can be represented as the following sequence of steps (Figure 1).

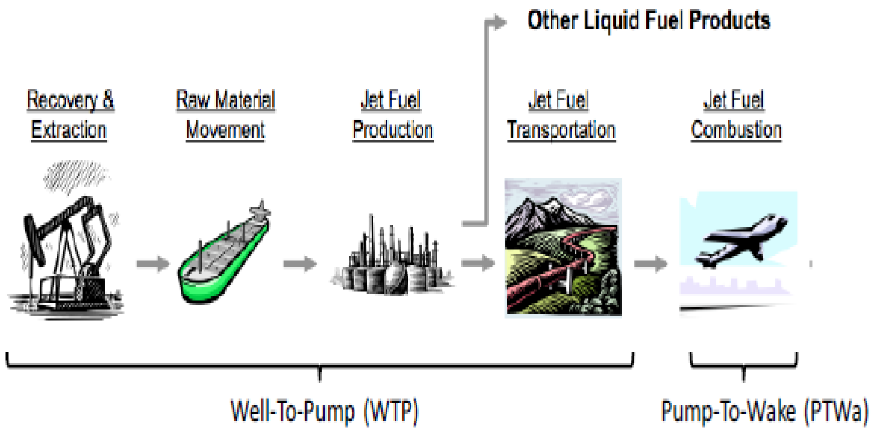

Fig. 1. Well-to-wake lifecycle for conventional fueled aircraft. ***Source: [9]***

LCA takes into account the extraction and transportation of raw materials (crude oil), processing of raw materials, transportation of finished fuel to the place of consumption, and fuel consumption during air transportation. In addition, in the full life cycle, it is also necessary to take into account the branch associated with the production of the aircraft itself, consisting of the stage of extraction and production of the necessary raw materials, aircraft production, and its maintenance during operation and disposal. However, knowing that the aircraft has been in operation for a rather long time, and the main negative environmental effects are produced due to fuel consumption, the contribution of this branch to the total negative environmental effect reduced to a unit of transport work is negligible.

That is, bringing all the negative environmental effects of the life cycle of fuel and the life cycle of an aircraft to a functional unit, the following expression will be obtained:

$$\left[\frac{(E_{ex}+E_{trans}+E_{ref})}{V_f}+E_{f\_comb}\right]\times k+\frac{E_{man\_a}+E_{serv\_a}}{S_{total}\times L} \quad (1)$$

where;

E_{ex} - negative environmental effects of oil extraction (per unit); E_{trans} - negative environmental effects of oil transportation (per unit); E_{ref} - negative environmental effects of oil refining (per unit); V_f - the amount of fuel produced from the unit of oil; E_{f_comb} – negative environmental effects of burning a unit of fuel; k - fuel consumption ratio for the production of the unit of transport work; E_{man_a} – negative environmental effects of the aircraft manufacturing process; E_{sev_a} - negative environmental effects of the aircraft maintenance process; S_{total} - total distance traveled by the aircraft for the duration of its operation; L – coefficient determining the average aircraft load (tonnes).

The magnitude of the second term in (1) is small compared to the magnitude of the first term and is not taken into account in many studies presented in modern literature. In addition, the process of production of the aircraft and its negative environmental effects remain approximately the same even in the case of a fuel change. This is generally true when using hydrogen as a jet fuel. For the case of using electricity as jet fuel, it is necessary to further take into account the negative environmental effects of batteries production, as it may in some cases be potentially environmentally hazardous. WTWa with hydrogen fuel is shown in Figure 2.

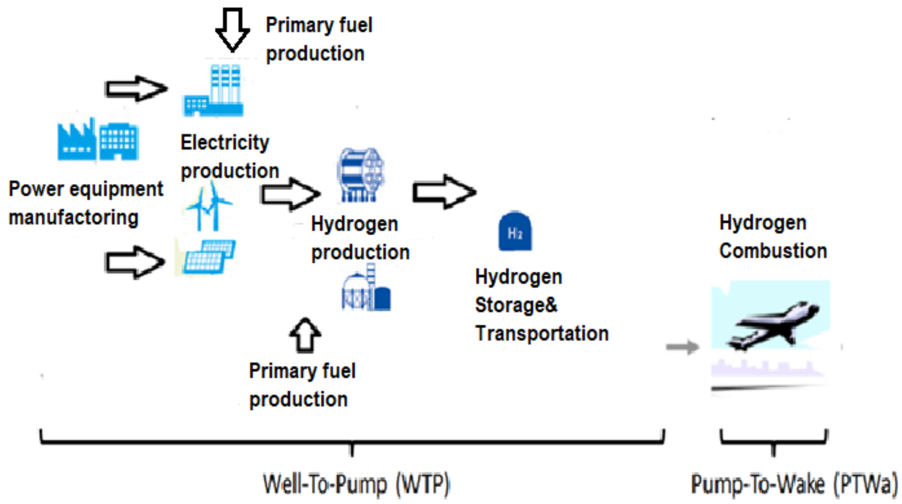

Fig. 2. Well-to-wake lifecycle for hydrogen fueled aircraft. ***Source: authors own***

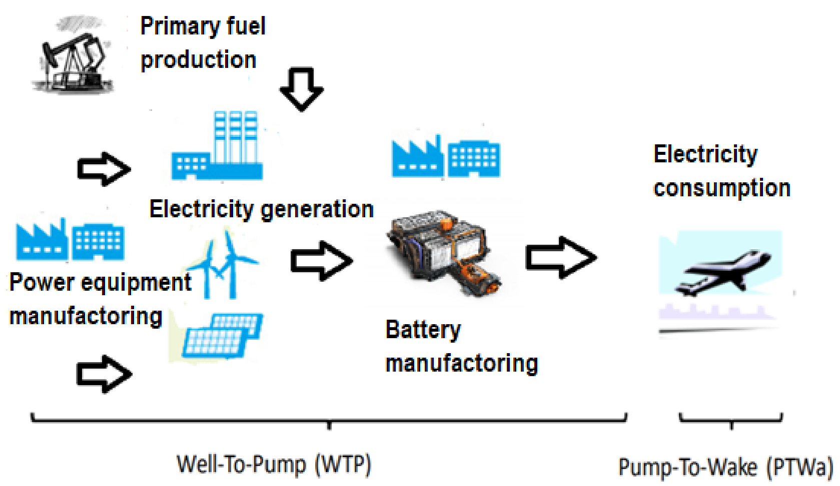

Fig. 3. Life cycle "from well to wake" for electricity as fuel. ***Source: authors own***

This life cycle has two main branches depending on the method of hydrogen production - steam reforming or electrolysis. At the same time, the branch corresponding to electrolysis, as the most energy-intensive production process, can be divided into two sub-branches - electric power production by traditional methods (due to hydrocarbons) and electric power production from alternative sources (solar and wind energy as the most mature technologies). In addition, it can also branch out during the storage and transportation of hydrogen, but at the moment these options have not been studied enough to carry out a life cycle assessment for all major categories of environmental impact. In the final calculations, this stage was not included, *i.e.* calculations were made under the assumption that hydrogen production is carried out near the place of its consumption (within a radius of 100-150 km) and in volumes that exclude the need for seasonal storage.

WTWa of all-electric aircraft is shown in Figure 3. Here, as in the previous life cycle, the process of generating electricity can be viewed along two branches — using traditional and alternative generation technologies. Both options were considered in the calculations. The effects of power transmission were not taken into account, *i.e.* it is assumed that the source of generation is located near (within a radius of 100-150 km) the place of electricity consumption.

The life cycle assessment of various types of fuel was carried out according to the CML 2001 method [24], which takes into account the widest possible range of negative environmental impacts, dividing them into categories (Table 1).

Table 1. Categories of environmental impact and methods of their measurement according to CML2001.

Category/units	Description
Oxidation (universal oxidation potential)/ kg SO_2-eq	Increasing the concentration of hydrogen ions lowers the pH of the environment and affects the biosphere. The main chemical oxidizing agents are SO_2, NO_x, HCl and NH_3. The oxidation potential is based on the amount of hydrogen ions produced per kg of chemical associated with SO_2. Acid gases react with water in the atmosphere and thereby form “acid rain”.
Eutrophication (potential deterioration of water quality in open waters)/ kg PO4-eq or NOx-eq	Eutrophication includes the potential effects of macronutrients, the most important of which are nitrogen and phosphorus. Increasing the nutrient content can cause undesirable changes in species composition and biomass increase in both aquatic and terrestrial ecosystems.
Stratospheric ozone layer depletion/ kg CFC – 11 – eq	With the reduction of the ozone layer, a higher amount of ultraviolet radiation penetrates to the surface of the Earth, which negatively affects the biosphere. The main factors of thinning the ozone layer are substances containing chlorine and bromine. All of them are associated with representative substance for this category – trichlorofluoromethane (CFC–11).
Climate change/ kg CO_2-eq	Emissions of certain types of gases (carbon dioxide, CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases) cause a greenhouse effect, which causes climate change, desertification, sea level rise and the spread of diseases. The global warming potential is the potential that determines the radiative (warming) effect of a particular greenhouse gas molecule relative to the CO_2 molecule. The effect of the release is estimated over a period of 20, 100, and 500 years, the most common being an estimate of 100 years. Carbon dioxide was taken as a reference gas.
Ecotoxicity (human ecotoxicity, fresh and sea water and sedimentary ecotoxicity), kg 1.4–DCB–eq	The most toxic substances are heavy metals (especially 6 – valent chromium, mercury, lead, nickel, copper, dioxins, barium and antimony). The impact of all elements is calculated on the equivalent of dichlorobenzene (1,4 – DCB). Dichlorobenzene is an organic compound that has a detrimental effect on human, animal and plant health.
Ionic radiation/ DALYs	Includes X-ray, alpha, beta and gamma particles. Ionizing radiation is presented in DALYs (shortened life expectancy). DALY is defined as the difference between the years lived and the life years lost due to the effect of atomic radiation.
Land use/ sq.m/year	The size and location of occupied land is important because reducing the natural development of ecosystems leads to a decrease in biodiversity.

3.2 Baseline and Assumptions

In this study, the authors used the data from the EcoInvent aggregator. Currently, EcoInvent is the world's leading LCA database in accordance with ISO 14040-14043 and contains data sets for the life cycle of more than 12,800 products and services, collected on the basis of real data on environmental effects, energy intensity and costs of products currently operating in various industries. A distinctive feature of EcoInvent is the matrix structure, due to which the automatic recalculation of environmental impact assessments of the product life cycle occurs when new data appear for a particular stage of the life cycle.

For new technological chains that are not yet industrially mastered and cannot be estimated based on real data, an independent analysis of the results of laboratory and experimental studies was carried out, and corporate reports from leading manufacturers were used as basic assumptions about performance, resource-intensiveness and other parameters of production processes, related products and services.

3.2.1 Data for assessment of the environmental and economic effects of hydrogen production as an aviation fuel

When analyzing the life cycle presented in Figure 2, the following main technologies for the production of hydrogen, which are at different stages of maturity, were considered:

1. Steam reforming of methane (or, alternatively, naphtha, liquefied natural gas (LNG)) is the most commercially mature technology.
2. Electrolysis of water - until recently was considered unpromising due to high energy consumption. However, this technology is becoming increasingly profitable when electricity is produced from renewable sources, especially when the amount of electricity produced is excessive and cannot be supplied to the grid. That is how the issue of storage of excess renewable energy can be solved. Nowadays this technology is industrially mastered.

Promising technologies that are at the stage of demonstration projects and laboratory research (production of hydrogen from hydrocarbons (methane, gasoline, naphtha, ethanol) directly on board the aircraft and splitting water under the action of solar energy using parabolic or flat solar cells) were not considered due to lack of primary data.

In turn, the technology of steam reforming and electrolysis, as the most commercially mature, have several modifications. So, for steam reforming technology, such variants are known as: (i) steam conversion using biogas [25]; (ii) steam conversion using coal gasification [26]; (iii) improved steam reaming technologies (with pre-ripping, heat recovery, *etc.*) [27].

For electrolysis technology is currently the most popular [28], [29]: (i) electrolysis using proton membrane electrolyzers (PEM); (ii) electrolysis using solid oxide electrolyzers (SOEC).

Technical characteristics of modern hydrogen production through steam reforming are based on estimates of one of the largest global hydrogen producers - Linde Group. In Table 2, they are calculated on the basis of the following characteristics of the finished product (hydrogen): the output flow rate is 50,000 Nm^3/h (here N stands for normal temperature and pressure), pressure – 2500,000 Pa, purity - 99.9 mole %.

Table 2. Technical and technological characteristics of hydrogen production by steam reforming.

Consumed resources	Parameters, units	Type of fuel			
		Natural gas	LPG	Naphtha	Refinery gas
Export steam	Flow rate, t/hr	31	28.9	28.6	29.2
	temperature, °C	390	390	390	390
	pressure, Pa	4000,000	4000,000	4000,000	4000,000
Fuel	Gcal/hr	177.8	181.8	182.9	175.8
	GJ/hr	744.4	761.2	765.8	736.0
Energy (including steam)	Gcal/1000 Nm^3 H_2	3.070	3.210	3.222	3.072
	GJ/1000 Nm^3 H_2	12.853	13.440	13.490	12.862
Water	demineralized, t/hr	55.6	57.5	60.6	53.2
	cooling, t/hr	160	165	168	157
Electricity	kW	850	920	945	780

Table 3. Technical and economic parameters of hydrogen production by PEM - electrolysis.

Parameter	Current Forecourt	Current Central	Projected Future Forecourt	Project Future Central
Capacity factor, %	86	86	97	97
Plant life, years	20	20	40	40
Total electrical usage, kWh/kg	54.6	50.3	54.3	50.2
Stack electrical usage, kWh/kg	49.2	46.7	49.2	46.7
Balance of plant electrical usage, kWh/kg	5.4	3.6	5.1	3.5
Total uninstalled capital, $/kW	940	450	900	400
Stack capital cost, $/kW	385	171	423	148
Balance of plant (BOP) capital cost, $/kW	555	279	477	252
Installation cost (% of uninstalled capital cost)	12	10	12	10
Replacement cost of major components (% of installed capital cost)	15	12	15	12
Replacement interval (years)	7	10	7	10

Source: [28]

Technical and economic parameters of electrolysis with proton membranes (PEM) are given in accordance with the source [28] and calculated for the two existing types of production - small-scale (hydrogen production 1,500 kg per day) and large-scale (production 50,000 kg per day) and under two forecast scenarios (for small-scale and large-scale production), taking into account the effects of learning-by-doing (Table 3).

Thus, a minimum estimation of energy intensity of PEM electrolysis as 50.2 kWh/kg of H_2 and maximum estimation as 54.6 kWh/kg of H_2 are obtained. These estimations will be used in the further calculations.

Technical and economic parameters of solid oxide electrolysis (SOEC) are also given in accordance with the source [28] for one operating type of production with a capacity of 50,000 kg of H_2 per day and a forecast production with technical improvements and of the same capacity (Table 4).

Table 4. Technical and economic parameters of hydrogen production by means of SOEC - electrolysis.

Parameter	Current	Future
Capacity factor, %	90	90
Balance of plant (BOP) lifetime (years)	20	20
Total energy usage, kWh/kg	50.9	46.6
Stack electrical usage, kWh/kg	34.0	34.0
System heat usage recalculated as kWh/kg	14.1	11.5
Total uninstalled capital, $/kW	820	430
Stack capital cost, $/kW	287	99
Balance of plant (BOP) capital cost, $/kW	533	331
Installation cost (% of uninstalled capital cost)	12	10
Effective annual stack service replacement cost (% of stack capital/year)	27.3	12.8
Stack service life (years)	4	7

Source: [28]

From data of Table 4, a minimum estimation of energy intensity of SOEC electrolysis as 46.6 kWh/kg of H_2 and maximum estimation as 50.9 kWh/kg of H_2 were derived.

At present, industrial technologies for transporting hydrogen use cylinders with the gas in a compressed state and tank containers in a liquefied state [30]-[32]. In this case, the main energy demand occurs at the stage of compression or liquefaction of hydrogen. For our further calculation the estimation of energy intensity of the process of liquefaction was taken from [31] as 12 (minimum) and 15 (maximum) kWh/kg of LH_2. Together with the estimations of energy intensity of PEM and SOEC electrolysis, an energy intensity of LH_2 production as 62.2 – 69.6 kWh/kg for PEM and 58.6 – 65.9 kWh/kg for SOEC technology were obtained.

To assess the impact of the life cycle of hydrogen produced by steam reforming and subsequent liquefaction, EcoInvent data was used. Estimates of the environmental impact of hydrogen production in the case of electrolysis as the main technology in the production process depend significantly on the structure of the energy balance. As shown in Figure 2, the study of the full environmental impact of hydrogen as jet fuel should be carried out based on the results of evaluations of various power generation options, including using modern renewable energy technologies.

Ecological effects on the main categories of environmental impact produced during the generation of 1 kWh of electricity by different generation technologies based on traditional (natural gas, as the most characteristic energy source for Russia) and renewable sources (solar and wind as the most commercially mature technologies) are presented in Table 5. The presented estimates of all environmental impacts for wind and solar energy are calculated as average values of several EcoInvent records. Thus, for wind energy four (4) records were considered: (i) for onshore turbines with a capacity of less than 1 MW; (ii) onshore turbines in the range of 1-3 MW; (iii) onshore turbines with a capacity of more than 3 MW, and (iv) offshore tubes of 1-3 MW. For solar energy 19 records were considered: multicrystalline silicon (m-Si), singlecrystalline silicon (s-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), copper-indium-diselenide (CIS), and ribbon silicon (r-Si) PV-modules of 3 kW with different ways of installation (facade, flat-roof, slanted-roof installation, integrated laminate, and a mounted panel). The estimates of environmental impacts for CCPP and conventional electricity generation from natural gas were taken from EcoInvent directly.

Note, that in this case all effects are taken into account in the full life cycle, *i.e.* including not only the stage of direct energy generation, but also the stages of production and installation of power equipment (photovoltaic panels, wind turbines, gas turbines), as well as the stage of extraction and transportation of fuel for thermal generation.

Table 5. The negative impact on the environment in the production of 1 kWh of electricity using modern technologies (taking into account the average capacity factor).

Category	Mean for wind energy	Mean for PV-technologies	Natural gas, CCPP	Natural gas, conventional
Climate change, kg CO_2-eq	0.0197	0.092	0.412	1.542
Oxidation, kg SO_2-eq	0.000143	0.000623	0.000572	0.00235
Eutrophication, kg NOx-eq	0.0000734	0.000287	0.000632	0.00168
Freshwater ecotoxicity, kg 1.4–DCB–eq	0.145	0.216	0.005	0.0256
Freshwater sediment ecotoxicity, kg 1.4–DCB–eq	0.352	0.506	0.012	0.0560
Human ecotoxicity, kg 1.4–DCB–eq	0.074	0.145	0.042	0.167
Land use, sq. m	0.00173	0.0086	0.0004	0.0025

Source: author's calculations.

Analyzing the data in Table 5, it can be noted that, in general, wind generation technologies are much more environmentally friendly than solar generation technologies, since their environmental impact is significantly lower in all major categories. As for the comparison of environmental impact indicators of renewables with gas generation technologies (both currently used and promising ones, *e.g.* combined cycle), it is difficult to draw unequivocal conclusions. On climate impact category, solar and wind energy have significantly less environmental effects; on the potential for eutrophication, and the oxidation potential, advanced gas generation technologies demonstrate the values of indicators comparable to those of solar energy, but worse than those of wind energy; on toxicity and land-use advanced gas generation technologies show a much better performance than not only PV, but also wind energy.

Considering these results and the estimates obtained for energy intensity of the electrolysis production processes as well as EcoInvent data on steam reforming, one can go directly to a comparative analysis of hydrogen fuel production technologies on environment. In order to do this to do this, the authors can simply multiply the amount of electricity consumed in the production of 1 kg of liquefied hydrogen by the indicators of all categories of environmental impact of each of the available technologies for the production of electricity. Taking into account the fact the obtained interval estimates for the energy intensity of electrolysis, estimates of negative environmental impacts will also be interval, *i.e.* in the range of minimum about maximum. At the next stage, the environmental impacts of air shipments with the use of hydrogen fuel by multiplying the obtained estimates by the value of fuel consumption (kg/tonne-km) of hydrogen aircraft from [20] (0.07 kg of LH_2 per tonne-km) were calculated. The results of comparisons with traditional fuel will be given in the Section 4.

3.2.2 Data for estimation of economic and environmental effects of using electricity as an aviation fuel

In this section, all calculations are based on assumptions about the energy efficiency of the Ce-Liner aircraft concept of Bauhaus Luftfahrt. The specifications of this conceptual model are shown in Table 6.

Table 6. Specifications of the Ce-Liner all-electric aircraft.

Aircraft properties	Values
Length (overall), m	43.0
Height (overall), m	12.9
Wing span, m	36
MTOW – maximum take-off weight, kg	109,300
MLW – maximum landing weight, kg	109,300
OWE – operational weight empty, kg	59,459
Range, km	1,667
Passengers	190
Maximum load (passengers + baggage + crew), kg	19,950
Batteries weight, kg	30,057
Batteries energy content, MWh	47
Electricity consumption per km, kWh	21.14
Electricity consumption	
per passenger-km, kWh	0.111
per tonne-km, kWh	1.06

Sources: [31] – [33] and author's calculations.

It should be noted that almost all of the parameters of the Ce-Liner electric aircraft, presented in Table 6 are still expected, but not yet achieved in reality. In particular, energy density is a key indicator for environmental and cost assessment of manufacturing chains for Ce-Liner's battery. The Ce-Liner concept sets high demands for the further development of battery technology at the most comprehensive integrated level in response to future top-level market requirements. The peak power demand for the propulsion system in the take-off flight phase is estimating as 33.5 MW, besides typical additional subsystem power demand gives plus 0.60 MW, that's giving maximum power demand about 34.1 MW. The cruise peak power demand is 15.6 MW for propulsion system and 0.95 MW for subsystems. The cruise phase of a flight for 1667 km distance (900 nm) takes 31.3 MWh for the propulsion system only, and take-off phase's energy requirement is 9.1 MWh. The total energy requirement for a flight is estimated as 47.0 MWh minimum (without a possibility to change airport if needed). All these technical requirements meet specific energy and power requirements specific of 1.7 kWh/kg and 1.2 kW/kg, respectively [33].

As noted above, the presence of high-capacity batteries (the production of which has a significant impact on the environment) distinguishes the life cycle of an all-electric aircraft (as an independent type of product) from the life cycle of an ordinary aircraft. Data on environmental effects of the full life cycle (without taking into account the utilization phase) of a 2.1 kWh lithium-ion battery with a voltage of 48 V are obtained from the EcoInvent database (Table 7, second column). All effects are designed for 1 kg of battery weight (dry mass). Assuming that the battery life cycle is 3,000 charging cycles (*i.e.*, 3,000 flights with a range of 1,667 km), these effects (*IC*) can turn into units of transport work by multiplying the environmental impact scores for 1 kg by the total mass of the batteries and dividing them by the full transport work over the entire life cycle and the maximum load of all-electric aircraft:

$$IC = IC_{kg} \times 30{,}057/(3{,}000 \times 1{,}667 \times 19{,}950)$$

The results of recalculations are presented in Table 7, third column.

Table 7. Ecological effects of lithium-ion batteries over the full life cycle.

Impact category/Unit	Value for 1 kg of dry mass	Value for tonne-km of transportation
Climate change, kg CO_2 – eq	7.3945	2.22769E-06
Oxidation, kg SO2 - eq.	0.099387	2.99416E-08
Eutrophication potential, kg NOx - eq.	0.038326	1.15462E-08
Freshwater ecotoxicity, kg 1.4–DCB–eq	20.661	6.2244E-06
Freshwater sediment ecotoxicity, kg 1.4–DCB–eq	40.832	1.23012E-05
Human ecotoxicity, kg 1.4–DCB–eq	45.474	1.36996E-05
Land use, m^2	0.54399	1.63884E-07

Source: author's calculations.

4. RESULTS AND DISCUSSION

Taking into account the obtained estimates of the environmental effects of hydrogen production, electricity production and production of batteries for electric power, the authors turn to the comparison of traditional and alternative types of aviation fuel over a full cycle (per ton-km of air transportation). To recalculate the environmental impacts of air transport on hydrogen fuel, the authors used the data from [16],[20] on the consumption of hydrogen fuel per tonnes-km (0.07 kg/tonnes-km). To assess the environmental effects of traditional jet fuel on the full life cycle and the various categories of environmental impact using EcoInvent data.

It should be noted that the impact assessments of traditional aircraft are more accurate, since they also take into account the impact of the airport infrastructure. The use of electricity as a fuel, on one hand, simplifies the infrastructure (storage and transportation of kerosene is not required), and on the other hand, complicates it (chargers are needed for batteries, containers for loading and placing them in the aircraft, modifying loading mechanisms). The use of hydrogen fuel significantly changes the infrastructure. It is not yet clear what contribution these changes have to the overall environmental load across the entire life cycle and across all categories of impact. In some literary sources, the contribution of airport infrastructure to the overall environmental effect is estimated to be from 30 to 44% [36]. However, as a rule, only one category of impact is taken into account - climate change. Therefore, in this study, no additional contribution that the ground infrastructure can make in assessing the environmental effects of alternative fuels has been taken into account. The results of comparisons of traditional fuels, taking into account the contribution of ground infrastructure and alternatives without regard to such contribution, are presented in Figures 4 to 7.

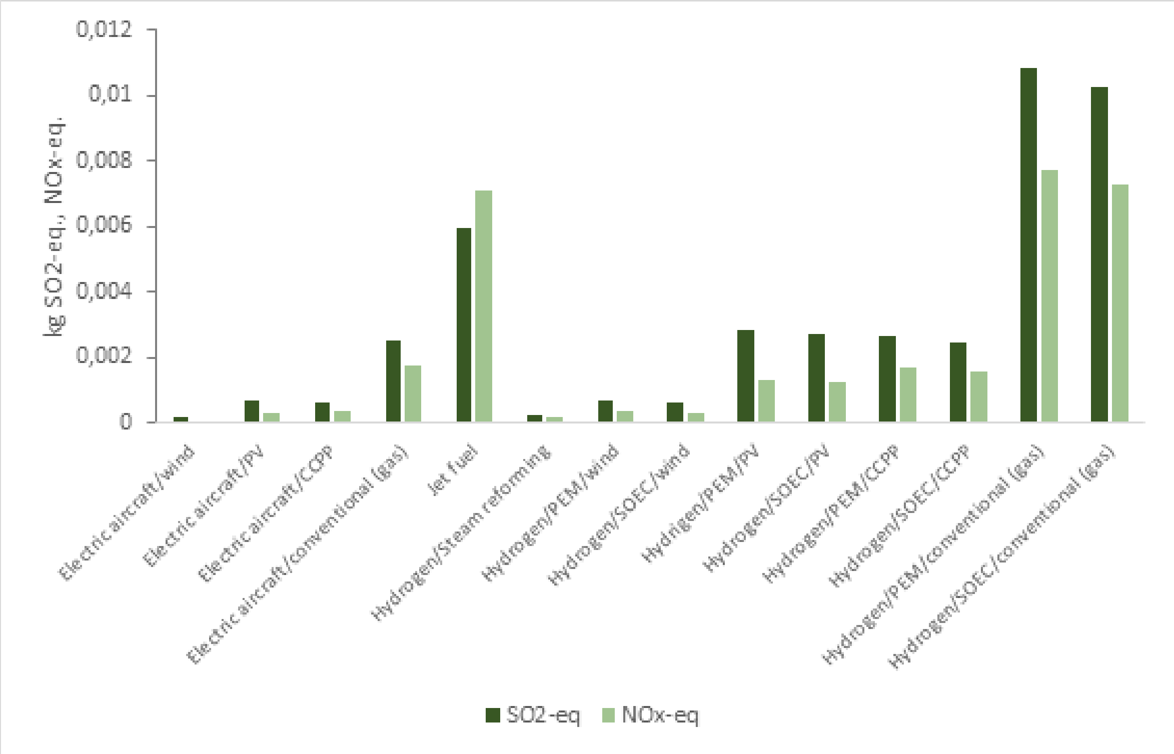

Fig. 4. Ecological effects of various types of aircraft on the full fuel and energy cycle in the category "Oxidation Potential" (kg SO_2 - eq.) and "Eutrophication Potential" (kg NOx - eq.) per tonne-km.
Source: author's own calculations.

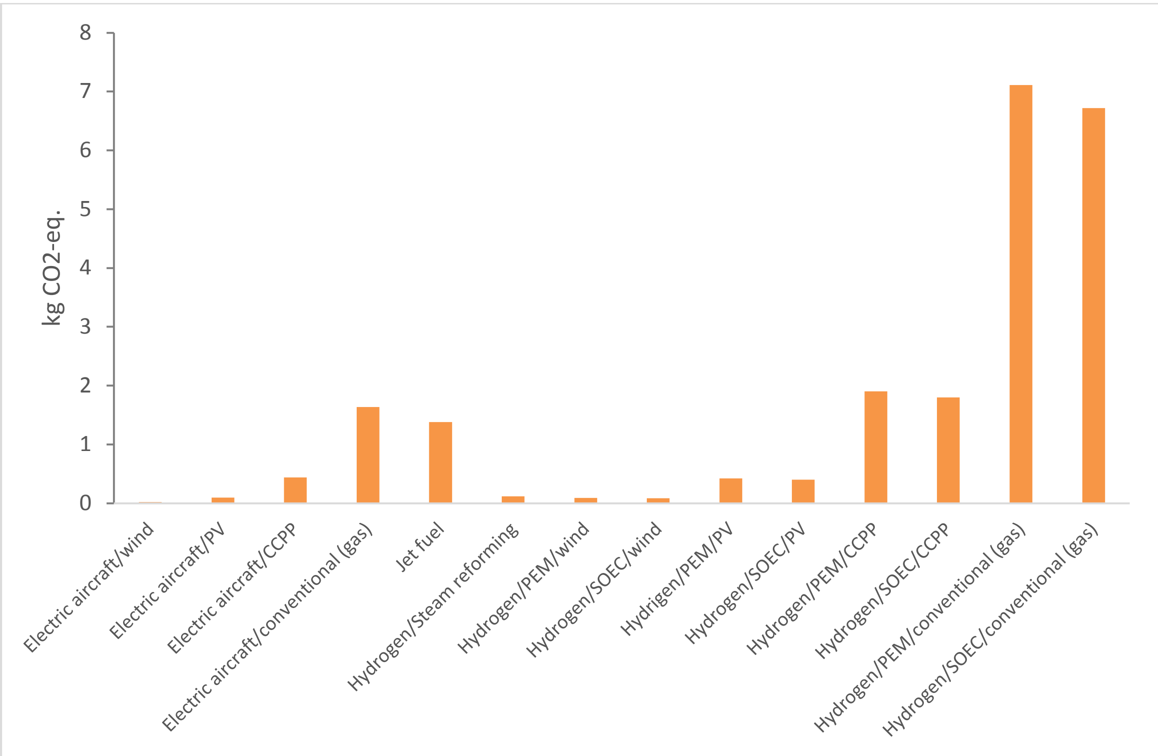

Fig. 5. Ecological effects of various types of aircraft on the full fuel and energy cycle in the category "Climate Impact", kg CO_2 - eq per tonne-km.
Source: author's own calculations.

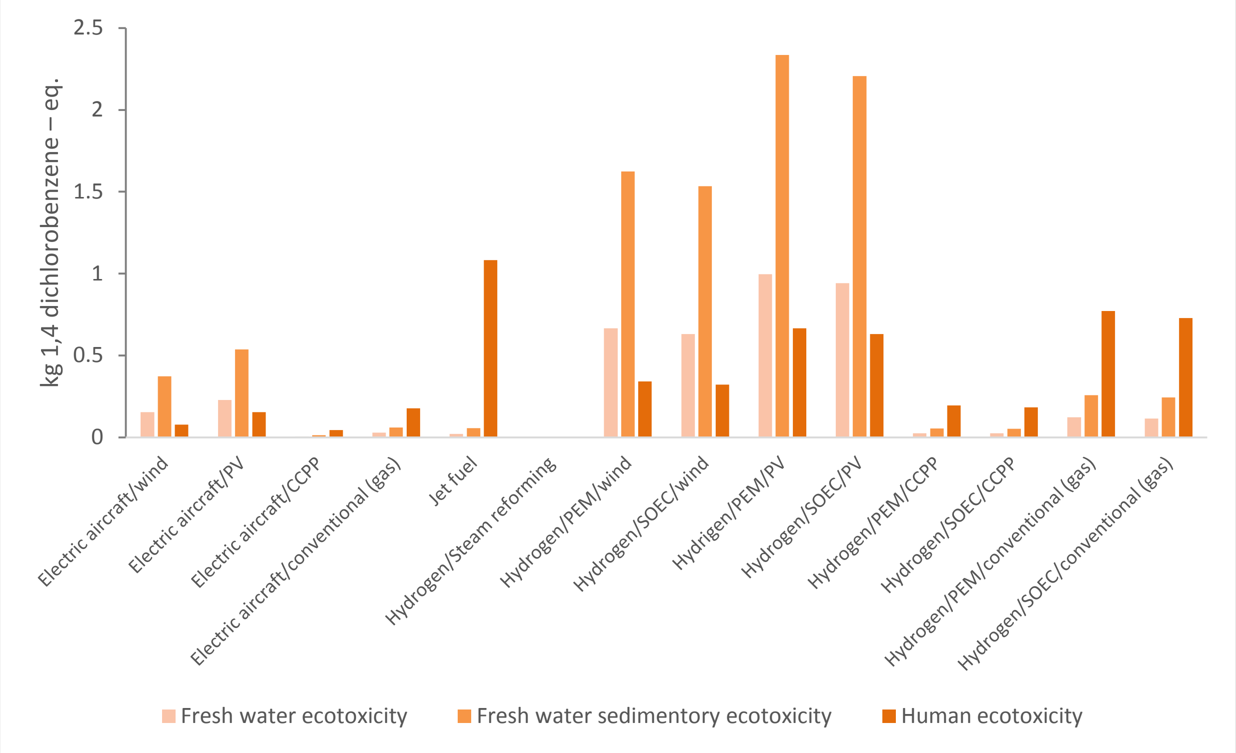

Fig. 6. Ecological effects of various types of aircraft on the full fuel and energy cycle by toxicity categories kg 1.4–DCB–eq per tonne-km.
Source: author's own calculations.

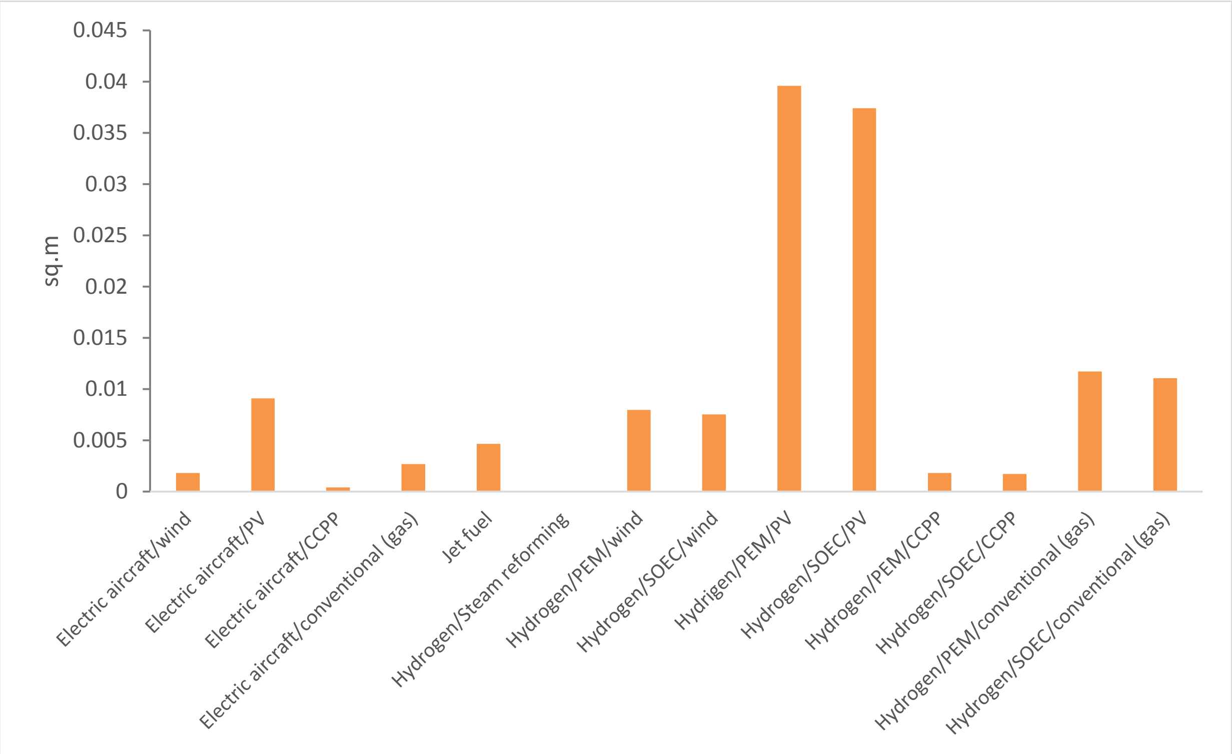

Fig. 7. Ecological effects of various types of aircraft on the full fuel and energy cycle in the category "Land Use", sq. m per tonne-km.
Source: author's own calculations.

From a comparison of the data presented in the diagrams, only one unequivocal conclusion can be drawn: hydrogen fuel is the most preferable alternative from an environmental point of view for all categories of environmental impact in case of using steam conversion technology for its production. The remaining alternatives do not have an unambiguous interpretation from the point of view of environmental preference, since they show different effects for different categories of environmental impact.

Comparing all the alternatives among themselves at a cost based on the data presented in EcoInvent (for industrially mastered technologies, in Euros, in 2005 prices) and introducing into account the additional interval component of the cost of ground infrastructure according to the source's assumptions [36], the results presented in Figure 8 were obtained.

Analyzing the results, the following conclusions can be drawn:

- taking into account the contribution of ground infrastructure + 20% of conventional cost, all alternative fuel and energy technologies are more expensive than traditional technologies of air transportation;

- the least significant increase in cost occurs in the case of using fully electrified aircraft, the most significant - in the case of using hydrogen fuel obtained by electrolysis.

From an environmental point of view, one of the most preferred alternatives in the medium term (considering the current level of development of renewable energy and aviation technologies) is the use of hydrogen, produced by steam reforming. On the long-term horizon (with the entry of fully electrified aircraft into the market), electricity, produced either by wind and solar generation, or by gas generation of a combined cycle also demonstrates high environmental performance. Moreover, according to the most important categories of environmental impact for human health (human toxicity, land use) gas generation of the combined cycle is the most preferred alternative.

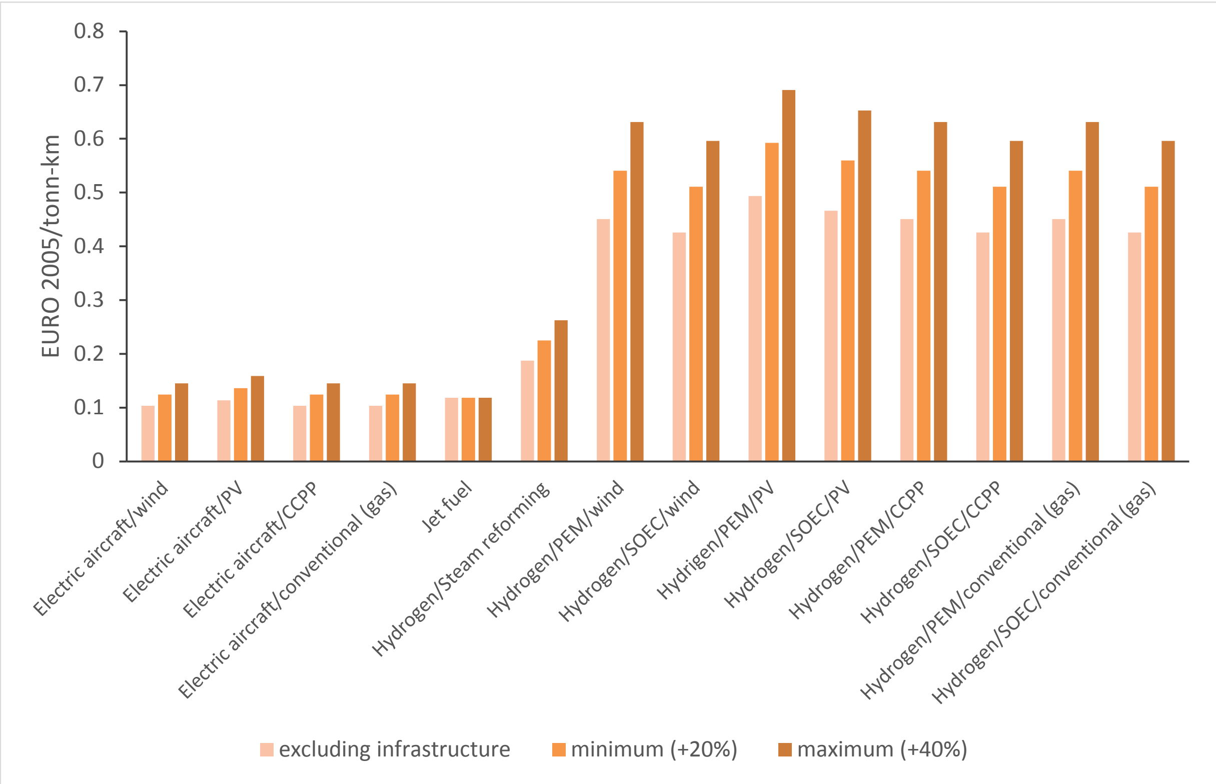

Fig. 8. Comparison of fuel and energy alternatives for costs (EcoInvent data, recalculation into units of transport work) without and taking into account the contribution of ground infrastructure.
Source: author's own calculations

5. CONCLUSION

The results of the study show that the technology of a fully electrified aircraft demonstrates the best balance of economic and environmental parameter in the case when wind energy, PV or CCPP are used to produce electricity. Moreover, for such countries as Russia, which have low prices for natural gas and developed gas power generation, this technology may provide additional advantages in terms of economic and social cost.

It should be recognized that the results of the study can only be considered as preliminary, because the assessment of the fuel and energy alternatives is viewed in a general sense, without reference to a specific regional energy system, which gives too much variation. The presence (or absence) of the ability to accumulate and use excess generated electricity from renewable sources (solar, wind) by producing hydrogen by electrolysis or charging batteries for power supplies will play a critical role in assessing the economic, environmental and energy parameters of each particular alternative in relation to the geographical and infrastructural features of a particular region. Increasing the capacity utilization factor of wind generators and solar panels will also have a significant impact on the cost and environmental effects of all transport and energy alternatives, in the production chain of which there are processes of electricity consumption.

Therefore, as priority areas for further research, the authors can point out an analysis of the production chains of the fuel and energy alternatives under consideration in relation to regions that can be considered as pilot for the use of alternative aviation fuels. In order to obtain more accurate estimates, a more detailed consideration of the local infrastructure of airport services (access to pipelines, distance from places with high classes of winds suitable for accommodating wind parks, *etc.*) is needed.

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