***Geopolitical transformations produce their impact on the cross-border regulation of hydrogen production and transportation. Russia's military aggression has blown up the global energy system and driven up energy prices. This exacerbated the issue of energy security, highlighting the excessive dependence of the EU on imports from the Russian Federation. These factors have accelerated Europe's transition to clean energy and increased hydrogen production.***

***The object of the research is legal relations in the field of development, transportation and storage of hydrogen in the territory of European states.***

***The results made it possible to propose mechanisms for reforming the legal regulation of the production and transportation of hydrogen across Europe. The vectors of the regulatory policy of European states are revealed, which should coordinate the increase in the potential of Ukraine in the regional leadership in decarbonization. It was stated that the legislative innovations of Ukraine are the basis for adaptation to EU practices.***

***The practical approbation of the changes in production practice declared by the states of Europe in the context of the global energy transition to a carbon-neutral society is substantiated. It has been established that reducing the cost of hydrogen and finding its wide application will become a global priority in the short term.***

***The basis of the hydrogen infrastructure has already been laid by including it in the renewed trans-European energy network. The issue of full-fledged approbation of production procedures in modern geopolitical conditions is debatable. Despite the hostilities, Ukraine continues the course of reforms by coordinating and arranging the purchase of hydrogen from renewable sources, which will allow full accession to the EU Energy Platform.***

***The results of the study can be used in the legislative sphere for a comprehensive reform of the national legislation of Ukraine***

***Keywords: green hydrogen, decarbonization of the economy, sustainable development, energy markets, hydrogen economy***

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# REFORM OF STATE REGULATION OF PRODUCTION AND TRANSPORTATION OF HYDROGEN ON THE TERRITORY OF EUROPEAN STATES IN THE CONTEXT OF EU POSITIVE PRACTICE

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## 1. Introduction

With the growth of the world's population, industrialization and urbanization, the demand for energy is growing rapidly, which requires a transition from fossil fuels to alternative environmentally friendly renewable energy sources [1]. About 85 % of the total energy consumption worldwide is obtained from non-renewable resources, namely coal, natural gas and oil [2]. The use of non-renewable resources contributes to an increase in environmental problems (global warming), economic and political crises.

Renewable energy sources include solar energy, biofuels, hydrogen, hydropower, tidal energy, ocean thermal energy, wind energy, geothermal energy, biomass energy, biogas, etc.

One example of a renewable resource is hydrogen, which plays an important role in supporting the reform of various sectors, such as industry, transport, electricity generation, etc. Hydrogen can be efficiently stored, transported and distributed at a low cost, making it an ideal energy carrier for a revitalized and sustainable society [3]. Hydrogen is particularly attractive for large-scale storage in power systems because it has a high gravimetric energy content and can be used together with fuel cells for backup power generation [4].

This substance has important potential to accelerate the process of expanding the use of clean and renewable energy, but its integration into energy systems remains poorly understood [5]. Although hydrogen is a zero-carbon energy source at the point of use, it depends on the cleanliness of the production route and the energy used to produce it. Thus, a guarantee of the origin of hydrogen is necessary in order to consider hydrogen as pure energy [6]. The main limitations to the widespread use of hydrogen are concerns about the overall life cycle cost and the perceived safety of the fuel. The main factors affecting the cost of hydrogen are the characteristics of the source from which it is extracted. In 2008, about 96 % of the hydrogen produced in the world was obtained from fossils, and since then this proportion has not changed significantly [4]. At the same time, 6 % of the world's gas and 2 % of the world's coal is used to produce hydrogen. As a result, hydrogen production is responsible for $CO_2$ emissions of around 830 million tons of carbon dioxide per year (International Energy Agency, 2019).

There are a large number of renewable sources used in the production of hydrogen, however, the volatile and unstable nature of these resources is a major challenge in the transition to a hydrogen economy. Therefore, this requires technical adjustments, especially to balance variable renewable energy sources, and the demand for variable energy. In addition, cost-effective production methods, policy, research and development, and the development of hydrogen infrastructure are industries that need additional research in the transition to a new type of economy [7].

Uncertainty about the speed with which the world is approaching the tipping point of climate change and the macroeconomic impacts of the Covid-19 pandemic makes it difficult to formulate reasonable expectations about the future value of the capital involved. So far, broad recovery programs after Covid-19 have paid special attention to «green» hydrogen [8]. Green hydrogen production can play a key role in connecting all energy-consuming sectors. This is the long-term goal needed to achieve the decarbonization of the economy. And for its successful implementation, a sufficient level of initiative at the national level is required [9].

The European Union, like many countries around the world, is facing challenges such as climate change and economic recovery from the Covid-19 pandemic. Therefore, the urgent task for these countries is the transition from the use of energy based on fossil fuels to renewable energy sources, including hydrogen. This position of Europe clearly indicates that the energy security component is currently being updated in the direction of unification of the European energy system. Therefore, the public sector of European states needs to create the appropriate balance capacities, implement important changes in the energy sector, including on issues related to the extraction, storage and transportation of hydrogen [10]. The above in its entirety actualizes the chosen research topic and requires additional scientific research in real life.

## 2. Literature review and problem statement

The work [1], devoted to the features of the production, storage and use of hydrogen, helped to find the relationship and interdependence between the relevant technical innovations. The analyzed heritage of the author made it possible to form the architectonics of the links between the economies of states and the sustainable development of regions. The work [11] contributed to the disclosure of the features of public administration in the context of the hydrogen economy and sustainable development goals. The work determined that the hydrogen economy is a promising vector for affordable clean energy supplies and deep decarbonization in industry. However, the issues of introducing the declared «green» innovations and decarbonizing the economies of states were considered by scientists mostly in fragments, without paying due attention to the context of the introduction of hydrogen into economic processes.

In [12], approaches to further prospects for the legal regulation of hydrogen are considered. Scientists were able to determine the possibilities of hydrogen production in the context of increasing the flexibility of the Ukrainian energy system. But the question of the legal basis for state regulation of these processes remained unresolved. Particular attention was paid to the work related to the concept of introducing «green» hydrogen in the EU [9]. The prospects outlined by scientists became the basis for the author's conclusions on the vector of the «green» economy, based on the innovative component with the hydrogen element.

The basic results of computational studies, design developments, tests and vectors of changes in public administration are presented in [6], which made it possible to study the ways of hydrogen production and related technologies.

The legal analysis of contrasting European hydrogen routes, variable approaches in key markets [13] made it possible to find a stable basis for the forthcoming rapid implementation of the declared European reforms aimed at refusing to cooperate with the Russian Federation in matters of fossil fuels. Deserving attention in the analysis of the above work and its comparison with the results of other scientific studies, the conclusions proposed by the authors regarding the production, distribution, storage and conversion of hydrogen in the hydrogen economy [4].

The work analyzed and took into account the general ideas of the EU hydrogen policy [14] and the vectors of the «green course» of the European Green Agreement [15]. Almost all EU member states recognize the important role of hydrogen in their national energy and have targets focused on transport and industry.

The analyzed material allows to state that it is advisable to conduct a study on the legal regulation of the production and transportation of hydrogen in European countries.

## 3. The aim and objectives of the study

The aim of research is to determine the legal basis for the production and transportation of hydrogen, taking into account the implementation of effective EU practices. This will make it possible to form clear vectors for the gradual implementation in practice of the declared concepts of decarbonization of the economy and the rational use of hydrogen in Europe.

To achieve the goal, the following tasks were set:

– to analyze the legislative innovations of the EU Member States in the field of hydrogen production and trans-

portation, to identify the most effective law enforcement practices;

– to group and establish the architectonics of legal acts that regulate the realities and prospects of decarbonization of the Ukrainian economy in the context of hydrogen use;

– to form proposals for improving the legal regulation in Ukraine in the area under study in the context of the gradual implementation of European experience.

## 4. Materials and methods of research

The object of research was legal relations in the field of development, transportation and storage of renewable gases (hydrogen) on the territory of Ukraine and the EU. The formation of a sample of scientific research was closely related to the multidimensionality of the chosen subject and the polyvariance of doctrinal approaches to the innovations proposed by the world community. Conditionally, the sample can be combined into the following groups:

1) sources were analyzed in the direction of the technical and economic basis for the development of technologies with the involvement of hydrogen;

2) the legal basis for state regulation of the production and transportation of hydrogen;

3) doctrinal sources with debatable provisions on the possibilities of introducing reformed public administration in the short term;

4) sources characterizing the foundations of interstate partnership on the way to the introduction of «green» hydrogen. The block diagram of the research methodology is shown in Fig. 1.

The following practical methods were used: observation, comparison, hypothetical-deductive method.

Through the method of observation, it was established that there is no mandatory methodology for calculating targets for the introduction of hydrogen into the economy in order to approach the declared indicators of the share of renewable energy on an EU-wide scale. The analytical comparison method showed a decrease in the total cost of pure hydrogen compared to previous periods, which leads to the introduction of the proposed qualitative changes in the implementation of public administration.

The comparison method made it possible to compare the fundamentals of legal regulation of the state administration of hydrogen production and transportation in the territory of the European Union and Ukraine, to reveal the correlation of their political and economic vectors. It was this method that showed Ukraine's inability to enter the European market as a supplier of green hydrogen. The comparison method was also used to understand the different levels of government regulation of hydrogen management in different jurisdictions.

The hypothetical-deductive method allowed, on the basis of the existing system of deductively related hypotheses, to reveal the prospects for transforming Ukrainian legislation on the way to adapting the European concepts of «green» hydrogen through the prism of public administration.

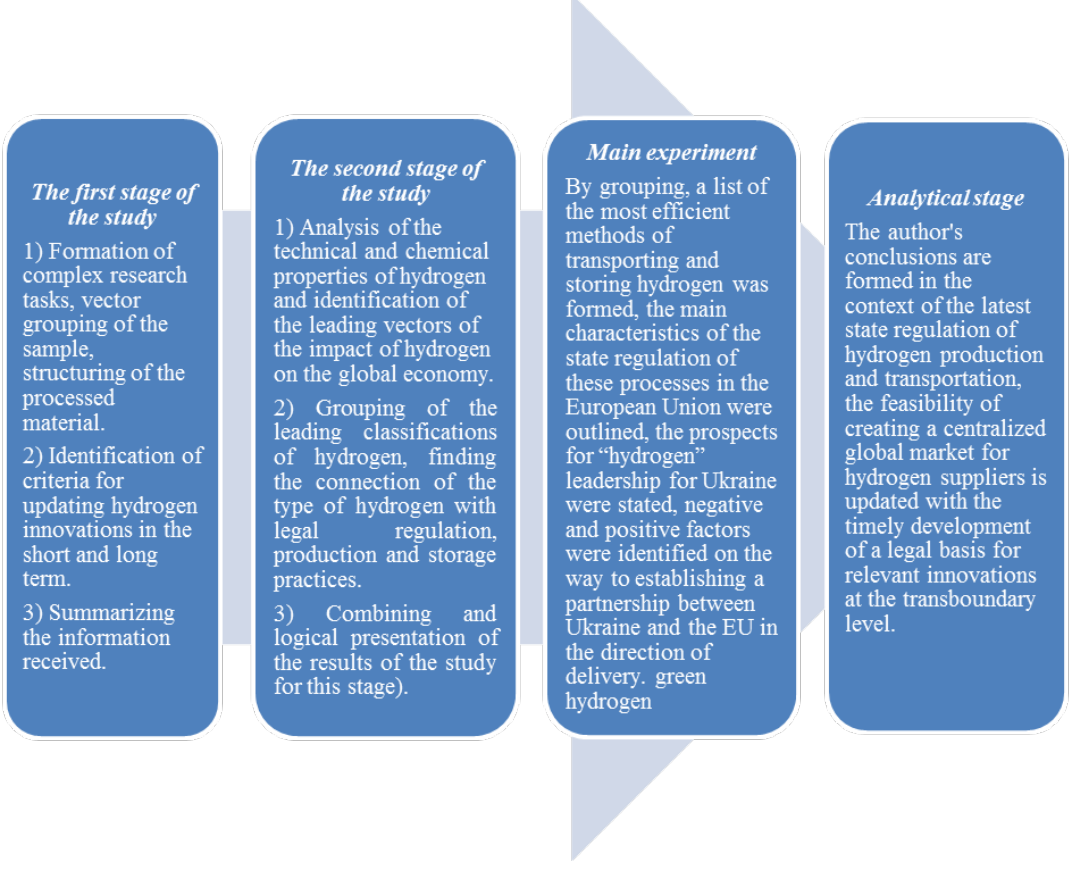


Fig. 1. Phased structure of the study

## 5. Results of studies of state regulation of production and transportation of hydrogen on the territory of Ukraine and the EU

### 5. 1. Legal framework and legislative innovations in the field of decarbonization in the territory of the EU and its Member States

The Paris Agreement [16], signed in 2016 by almost 200 countries, set the goal of limiting global warming to much lower, predominantly by 1.5 °C, compared to pre-industrial levels. If the world can keep climate change below 2 °C, by 2050 hydrogen will account for 18 % of total energy consumption, and in the EU this figure could reach 24 %. This trend will reduce the amount of $CO_2$ emitted into the atmosphere by 6 gigatonnes per year and at the same time create 30 million jobs in the industry worth 2.5 trillion dollars per year [17]. Global demand for hydrogen is projected to rise from 70 million tons in 2019 to 120 million tons by 2024. The development of hydrogen should also meet the seventh goal of the United Nations «affordable and clean energy» [18].

However, ensuring the implementation of global demand must be based on sound statistics. Thus, the energy balance, expressed in megatons of oil equivalent (Mtoe) for renewable energy and biofuels in the countries of the European Union, is disclosed in Table 1 [19].

Table 1

Energy balance of renewable energy sources and biofuels in the countries of the European Union (according to the EU Energy Statistics)

| – | 2016 (Mtoe) | 2017 (Mtoe) | 2018 (Mtoe) | 2019 (Mtoe) | 2020 (Mtoe) |
|---|---|---|---|---|---|
| Production | 203.31 | 210.25 | 219.92 | 227.29 | 234.17 |
| Import | 15.01 | 16.24 | 18.51 | 18.90 | 20.41 |
| Export | 11.16 | 11.85 | 13.27 | 14.15 | 14.33 |

It can be stated that the average share of energy consumed from renewable sources as a percentage for 2020 in 27 EU countries was 22.090 % [20]. Within each EU country, the situation regarding the share of energy consumed from renewable sources as of 2020 as a percentage is disclosed in Table 2 [20].

Thus, with more than half of energy from renewable so urces in gross final energy consumption, Sweden (60 %) has the highest share among EU Member States in 2020, ahead of Finland (44 %) and Latvia (42 %). The lowest share of renewable energy was registered in Malta (11 %), followed by Luxembourg (12 %) and Belgium (13 %). Renewable hydrogen should be the key to replacing natural gas, coal and oil in hard-to-decarbonize industries and transport in the European Union. Until 2030, the EU countries need to produce 10 million tons of renewable hydrogen within the EU and import 10 million tons of renewable hydrogen [21]. In this context, the legal basis for the implementation of the declared plans is of particular importance.

Thus, with more than half of energy from renewable soThere are four main stages of the hydrogen economy: production, storage, safety and use, where the choice of production method must take into account the purification and compression of hydrogen along with the assessment of the life cycle of hydrogen. The level of hydrogen purity is described by different colors (Fig. 2). It can be stated that the accurate measurement of greenhouse gas emissions throughout the entire production process, as well as the life cycle of the equipment used, is crucial.

Table 2

Shares of energy consumption from renewable sources in the European Union as of 2020 (according to Eurostat)

| Country | Share of energy consumed from renewable sources ( %) |
|---|---|
| Malta | 10.714 |
| Luxembourg | 11.699 |
| Belgium | 13.000 |
| Hungary | 13.850 |
| Netherlands | 13.999 |
| Poland | 16.102 |
| Ireland | 16.160 |
| Cyprus | 16.879 |
| Czech | 17.303 |
| Slovakia | 17.345 |
| France | 19.109 |
| Germany | 19.312 |
| Italy | 20.359 |
| Spain | 21.220 |
| Greece | 21.749 |
| Bulgaria | 23.319 |
| Romania | 24.478 |
| Slovenia | 25.000 |
| Lithuania | 26.773 |
| Estonia | 30.069 |
| Croatia | 31.023 |
| Denmark | 31.681 |
| Portugal | 33.982 |
| Austria | 36.545 |
| Latvia | 42.132 |
| Finland | 43.802 |
| Sweden | 60.124 |

Hydrogen is the most abundant element, and in terms of its reactivity, it only exists in the form of compounds such as water and organic materials. The use of hydrogen fuel leads to the integration of renewable energy sources into the existing fuel infrastructure and the elimination of greenhouse gas emissions. When hydrogen is burned, only water vapor is produced, thus it is considered the cleanest source of energy. It is a flammable and colorless, odorless gas, raising concerns about its safety, especially if no leak is found and the gas accumulates in a confined space. In addition, metal hydrogen crunching is a problem as it can damage pipelines and containers due to its small molecular size. Thus, hydrogen can permeate through materials. Although hydrogen gas has a high energy density by weight but a low energy density by volume compared to hydrocarbons, it requires a larger tank to store it. For example, unlike liquefied natural gas, liquefied hydrogen contains 2.4 times more energy, but requires 2.8 times more volume to store. At the same time, the low storage temperature of liquefied hydrogen at atmospheric pressure and a temperature of –253 °C creates many risks and can cause frostbite. In addition, a leak may result in the formation of a mixture of liquefied air and hydrogen, which will lead to the formation of an explosive mixture or the formation of flammable or explosive channels.

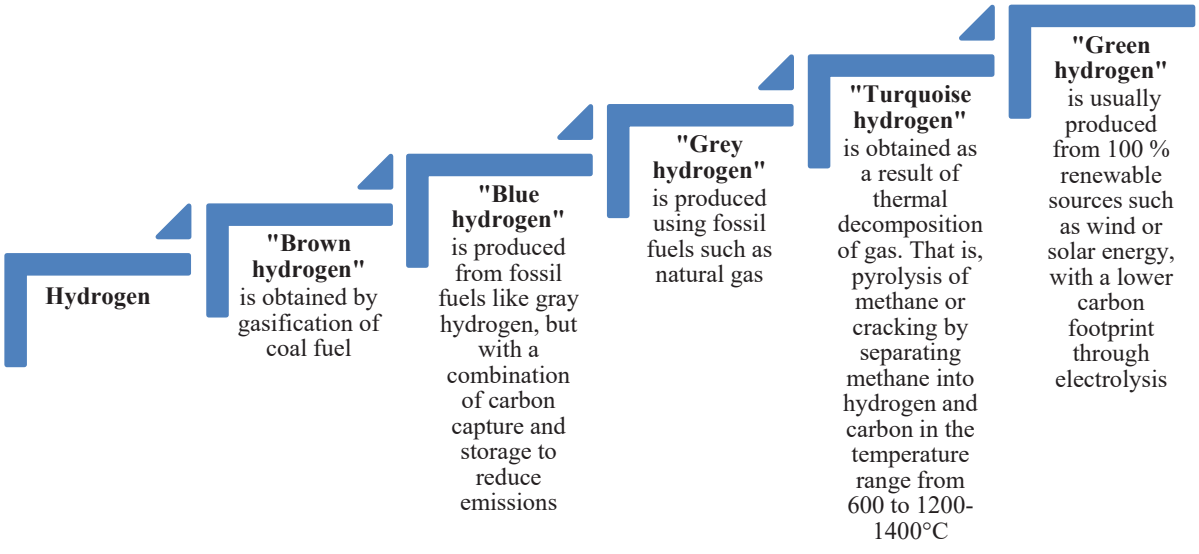


Fig. 2. Hydrogen purity levels

Hydrogen precautions include a combination of primary, secondary, and tertiary measures. Primary measures include the elimination of causal risks such as leakage and the formation of explosive mixtures through appropriate design (inerting, outdoor installation, flame arresters). Secondary measures are mainly aimed at avoiding ignition sources of any type (electrostatic or mechanical sparks). Tertiary measures include ways to minimize hazardous outcomes in the event of a fire or explosion. This is achieved through the installation of explosion-proof or anti-explosive systems, hydrogen process shutdown systems and appropriate fire extinguishing systems. The above measures are of maximum relevance in the production and transportation of hydrogen.

The main factors affecting the life cycle cost include production cost, delivery cost, market price, demand, storage costs, distribution costs and investment costs. There are existing and planned technologies for the production of hydrogen, some of which are focused on the steam reforming of fossil fuels, as well as steam reforming of gas. However, in order to minimize carbon dioxide emissions, a wider range of hydrogen extraction processes, such as methane pyrolysis and seawater electrolysis using alternative energy sources, must be considered. There are many ways to extract hydrogen from hydrous materials, both hydrocarbon and non-hydrocarbon, such as photonic, electrical, chemical, bioenergetic, thermal, and a combination of these methods together. However, the production of hydrogen will require large amounts of fresh water, and these reserves around the world are already depleted. Thus, the use of sea water will be one of the options for solving this problem. It can be stated that the main areas of water electrolysis that require further study are the reduction of capital costs for electrolysis technology, the search for water resources and the increase in efficiency.

The use of hydrogen for renewable energy storage is critical because it can be stored, used and transported. Transport conditions vary. The most typical ones are shown in Fig. 3.

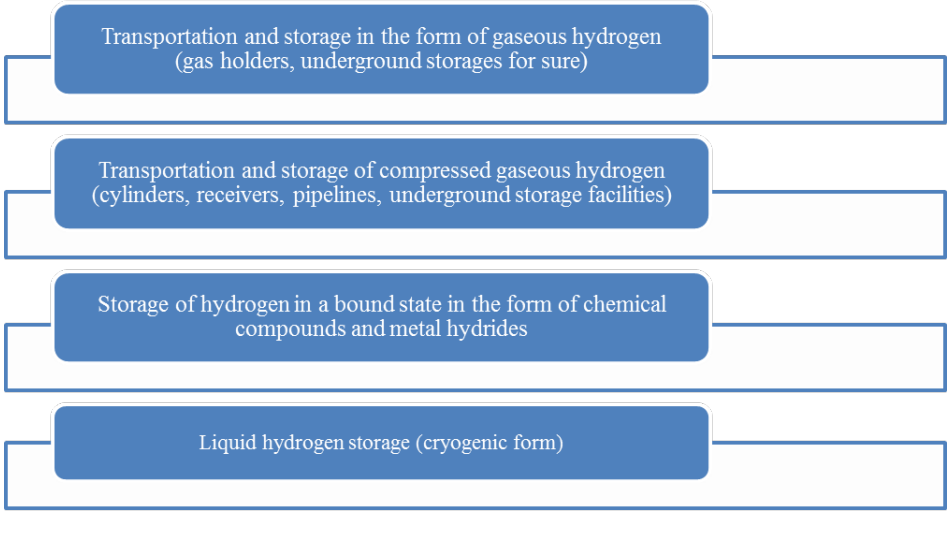


Fig. 3. Variable methods of hydrogen storage and transportation

A promising method for the simultaneous storage and transportation of hydrogen is hydrogen pipelines, which, despite the rather high costs of their installation, are the cheapest way to store and transport hydrogen. This method of storage and transportation appears to be the most efficient for use in power generation or as feedstock in energy-intensive industrial sectors such as oil refining, ammonia, methanol and steel production. Hydrogen can be used in transport in internal combustion engines: reciprocating engines; gas turbines; the inclusion of a turboelectric distributed power plant. Possible applications of hydrogen include rail transport, road transport, aviation, shipping, public utilities and other areas. In public and commercial road transport, hydrogen also proves to be more profitable than electric vehicles, since the charging time and weight of the batteries required for electric vehicles are not always economically feasible. Therefore, the development and operation of hydrogen filling stations is very relevant now. In buildings, longer term prospects may include the direct use of hydrogen in hydrogen boilers or fuel cells.

As relevant markets, hydrogen transportation and stationary energy sources grow, codes and standards are emerging to help ensure safety. Efforts have been made by the European Union to harmonize these documents with the global market in mind, harmonizing them with international norms. In particular, emphasis is placed on the implementation of international standards in the area under study [22–24]. The content of these documents includes a reflection of the problems associated with hydrogen energy, the implementation of existing standardization initiatives, an analysis of the current state of technology and standardization. There are also recommended actions to address gaps and problems, and means for appropriate implementation.

The European Union is taking the lead in the development of hydrogen energy systems. It also has great market potential for further profitable business. More than 300 companies in the EU are active in the fuel cell and hydrogen sectors, and many more in their respective supply chains [3]. Many feasibility studies of existing facilities operating on hydrogen have confirmed the economic feasibility of hydrogen energy systems, taking into account all direct and indirect costs. The European Green Deal [17] defines hydrogen as a source of a clean circular economy. The European Union has released a dedicated Hydrogen Strategy [25], which combines measures to promote the rapid and targeted development of green hydrogen production capacity. Also, within the framework of the European Green Deal, the Energy System Integration Strategy was adopted [26]. This strategy was an important step in shaping the transition vector of European energy markets by 2050. It has made a significant contribution to clarifying the EU's approach to key issues such as electrification, the role of gas in the future energy mix and energy infrastructure.

On July 14, 2021, the European Commission presented a package of legislative initiatives «Fit for 55» [15]. Accordingly, EU policies on climate, energy, land use, transport and taxation are consistent with a reduction in net greenhouse gas emissions of at least 55 % by 2030 compared to 1990 levels. This initiative, under the recently adopted EU Climate Act [27], aims to ensure the necessary acceleration in the reduction of greenhouse gas emissions in the next decade. It presents measures to prevent carbon leakage and tools to conserve and increase natural carbon sinks.

In 2018, the EU Renewable Energy Directive 2018/2001 [28] was adopted, which included the legal designation of non-biological renewable liquid and gaseous transport fuels, including hydrogen. The directive set EU-wide target for the share of renewable energy of 32 % to be achieved by 2030. Member States had to implement it on their territories, taking into account national interests and ambitions, the availability of raw materials and production capacities. In accordance with the Fit for 55 initiative, proposals have been made to this Directive [29] 557 final, 2021). The updated EU target of at least 32 % renewable energy by 2030 set in the Renewable Energy Directive [28] is insufficient and should be increased to 38–40 %.

In 2014, Directive 2014/94/EU of the European Parliament and of the Council on the deployment of infrastructure for alternative fuels was adopted [30]. On March 8, 2021, the European Commission stated the absence of a mandatory methodology for calculating targets and taking measures, the presence of different levels of ambition in setting targets and supporting policies between Member States [31]. The Commission has also proposed cutting greenhouse gas emissions by at least 55 % by 2030, compared to previous targets of 40 %. In line with the Fit for 55 initiative, proposals have also been made to this Directive [29] in order to increase ambitions to combat climate change.

The fuel quality directive 98/70/EU [32] indirectly stimulated the use of hydrogen. According to this document, fuel suppliers were required to reduce their life cycle greenhouse gas emissions per unit of energy by 6 % by December 31, 2020. It was supplemented by Council Directive (EU) 2015/652 [33], fixing the efficiency of electric propulsion on hydrogen fuel cells at 40 % and the intensity of greenhouse gas emissions of pure and fossil hydrogen and methane derived from hydrogen.

On April 21, 2021, the European Commission approved a draft Delegated Regulation [34], which establishes technical criteria, including for hydrogen, according to which various types of economic activity significantly contribute to climate change mitigation and adaptation. It should be noted that the HyLaw project [35] identified in 2019 more than 50 EU legislative acts in broader areas of regulation that indirectly affect the development of hydrogen technologies and should be considered. These include health and safety, environment, labor and transport. The EU supports hydrogen research and innovation projects under the Horizon 2020 and Horizon Europe research frameworks (2021–2027). The projects are managed by the Fuel Cell and Hydrogen Joint Venture (FCH JU), a public-private partnership supported by the European Commission. More than 1 billion euros have been invested in hydrogen projects [13]. The second phase of FCH JU (2014–2024) is expected to receive EU support of 665 million EUR, which, supplemented by private financing, will bring investments of more than 1.3 billion EUR [14].

On June 2, 2021, the European Commission, together with Australia, Austria, Canada, Chile, Germany, India, Italy, Morocco, Norway, Saudi Arabia, South Korea, the United Kingdom and the United States, agreed on a Clean Hydrogen Mission [36] to advance all the world. The purpose of this agreement is to reduce the total cost of pure hydrogen to 2 USD per kilogram.

EU countries pay great attention to the role of hydrogen in national decarbonization programs. Germany's national hydrogen strategy [37] aims to achieve a production capaci-

ty of 5 GW by 2030 and 10 GW by 2040. Significant funding has been allocated for research and technology transfer from the lab to the market, including separate funding for industry. Recognizing the limitation of the production of hydrogen needed in Germany, a budget of 2 billion EUR was proposed to develop an international partnership. The German federal government has unveiled a comprehensive strategy aimed at accelerating the growth of the green hydrogen market and thus decarbonizing the German economy. At the same time, the German federal government realized in advance that the country would be dependent on the import of a significant amount of «green» hydrogen, especially in the medium and long term. Accordingly, a global market for hydrogen suppliers will be created in the near future. To this end, measures No. 34–38 of the German National Hydrogen Strategy [38] focus on international cooperation in the field of hydrogen. In 2021, Germany approved a Federal Government Ordinance providing for the exemption of green hydrogen projects from the fee payable under the German Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG), and an amendment to the German Energy Act , establishing the regulatory framework for hydrogen networks in Germany[38].

In 2020, Portugal and the Netherlands signed a memorandum of understanding regarding their intentions to connect their respective hydrogen production plans [39]. The Dutch national plan includes the production of «blue» hydrogen from gas through carbon capture and storage; however, the northern Netherlands region has opted for 100 % renewable hydrogen in its recent regional hydrogen strategy [14].

**5. 2. State regulation of production and transportation of hydrogen in Ukraine**

The potential of installed capacities for renewable energy sources in Ukraine is projected at 874 GW, of which 688 GW is wind energy and 82.76 GW is solar energy [40]. As for the level of green hydrogen production in Ukraine, according to the baseline scenario, the renewable energy potential of Ukraine is 537 GW of installed capacity. Based on these figures, the potential for the production of «green» hydrogen in Ukraine is 505.133 million cubic meters [41].

It is extremely important for Ukraine to add «green» hydrogen to natural gas, using the already existing main pipelines for transporting natural gas. In the Hydrogen Strategy (Hydrogen Strategy for Climate Neutral Europe, 2020) [25], the EU assesses Ukraine as the main partner in the supply of hydrogen, taking into account the natural potential, interconnected infrastructure and technological development of this state. According to the plan of European companies «Green Hydrogen for the European Green Deal: 2×40 GW Initiative» (Hydrogen Europe 2×40 GW Initiative, 2020), European companies aim to build 40 GW of electrolysis hydrogen production capacity in EU countries by 2030. The same number is outside the EU, including in Ukraine (up to 10 GW). The corresponding growth of the hydrogen market will be able to significantly reduce the cost of green hydrogen production technologies. In this connection, according to the estimates of the Institute of Renewable Energy of the National Academy of Sciences of Ukraine [42], an important direction is the adaptation of 67 European standards in the hydrogen industry to the legislation of Ukraine. The following national hydrogen standards have been adopted in Ukraine: DSTU ISO 14687:2021 (ISO 14687:2019, IDT) Hydrogen fuel quality. product specifications; DSTU ISO/TR 15916:2021 (ISO/TR 15916:2015, IDT) Basic provisions for the safety of hydrogen systems; DSTU ISO 22734:2021 (ISO 22734:2019, IDT) Hydrogen generators based on water electrolysis. Industrial, commercial and domestic programs [43].

The gas transportation system (GTS) of Ukraine includes more than 33 thousand km of pipelines, 57 compressor stations, 33 gas metering stations and 1389 gas distribution stations. Now there is no long-term perspective of gas volumes and full guarantees of the continuity of transit in connection with the possible commissioning of the Nord Stream 2 gas pipeline from Russia to Germany across the Baltic Sea with a length of 1234 km. In this connection, there is a need to optimize and reduce the scale of significant sections of the Ukrainian GTS. Sections of the network must be re-equipped for future gas flows in a west-east direction so that Ukraine can import gas from Europe. Reducing the capacity of the Ukrainian GTS will also reduce or eliminate the possibility of transporting hydrogen or other renewable gases from Ukraine to Europe.

Hydrogen remains an important part of the energy mix for European industrial sectors that cannot be electrified. The acceleration of research and innovation in the field of hydrogen and ammonia has become even more relevant in the situation of the military conflict in Ukraine. The scale required by global change also needs significant reforms. First, it is predicted to decarbonize all the «grey» hydrogen production today, which entails carbon emissions, and then scale the market for pure hydrogen solutions. While increasing gas imports today is a short-term solution for Europe, investing in tomorrow's hydrogen solutions to balance demand and production markets is an important part of future energy reforms and international agreements. The EU's call for 10 million tonnes of renewable hydrogen domestic production and 10 million tonnes of imports by 2030 is a key step towards replacing the use of oil, natural gas and coal for hard-to-decarbonize industries.

It is worth noting that on June 5, 2022, National Joint Stock Company Naftogaz of Ukraine entered into an agreement with Canadian energy developer Symbio Infrastructure (Symbio) for the purchase of liquefied natural gas (LNG) and green liquid hydrogen (LH2) in Quebec, Canada. This agreement will be the key to the long-term strengthening of the energy independence of Ukraine. Energy from Symbio's innovative infrastructure will provide competitive energy to Ukraine and significantly reduce global greenhouse gas emissions by displacing higher emission energy sources used in Europe.

**5. 3. Promising vectors of legislative innovations in Ukraine in the field of production and transportation of water in the context of EU practices**

Ukraine should seriously work on the re-profiling of the GTS so that its gas transmission capacities do not remain on the sidelines of the relevant movement for decarbonization and investment programs of the EU. Today, Ukraine lacks the infrastructure that is needed for the production of «green» hydrogen. Pipes intended for gas must be adapted for the respective transport. It is necessary to create economic conditions for stable production in the country. There is also a need for more investment in this industry. In this connection, Ukraine needs to decide on the regulatory framework for the new necessary reserve capacity. They

are likely to be based on natural gas with the possibility of flexible use of fuel for the subsequent transition to hydrogen.

The Energy Strategy of Ukraine until 2035 [44] and the National Transport Strategy of Ukraine for the period until 2030 [45] do not contain a mention of hydrogen as a result of the adoption of these documents to include hydrogen energy issues in the priority agenda of the Ukrainian government. The Law on the Natural Gas Market [46] does not define and regulate «green» hydrogen, the Law on Alternative Energy Sources [47] does not regulate the use of renewable energy sources for the production of «green» hydrogen.

In 2021, the Energy Security Strategy of Ukraine [48] was adopted, in which hydrogen energy is presented in the context of the development of the scientific, technical and innovative potential of Ukraine for the needs of the energy sector. The climate orientation of the tasks of hydrogen technologies is presented in the Low-Carbon Development Strategy until 2050 [49], approved on July 18, 2018 by the Cabinet of Ministers of Ukraine. It notes the industrial production and use of hydrogen as a component of the policy of introducing innovative technologies in the energy sector and the use of alternative types of motor fuel. It should be noted that Ukraine is currently developing a draft Law of Ukraine on the Low-Carbon Development Strategy for the period up to 2050 [50]. An important step in this direction was the approval of the Updated Nationally Determined Contribution of Ukraine to the Paris Agreement [51]. This implies the need to reduce greenhouse gas emissions by 2030, including through the development of renewable energy sources, to a level of 35 % compared to 1990.

In March 2021, at the request of the Ministry of Energy of Ukraine and the State Agency of Ukraine for Energy Efficiency and Energy Saving, projects of the Roadmap for the production and use of hydrogen in Ukraine [52] and the Roadmap for the use of hydrogen in Ukraine in the field of road transport were presented in Ukraine [53]. These projects were prepared with the help of the United Nations Economic Commission for Europe under the project «Strengthening the Ukrainian government's capacity to develop infrastructure for the production and use of hydrogen to support a green recovery after Covid-19».

According to the Roadmap [52], it is necessary to take actions and activities at the national level. It is advisable to cite the basic principles for the introduction of hydrogen technologies in Ukraine, enshrined in this document: transformation of power supply and heating systems; conversion of heat released during the production process; transformation of the transport sector; GTS of Ukraine and a gradual increase in production, storage and transportation of hydrogen. The draft Roadmap for the production of hydrogen in Ukraine [52] provides for three stages of implementation with a detailed description of legislative changes and economic measures. The first stage from 2021 to 2023 is dedicated to the analysis of the Ukrainian economy on the «green transition» and the launch of the hydrogen economy. The second phase from 2024 to 2026 is dedicated to policy priorities, the hydrogen market and the development of the hydrogen supply chain. The third phase from 2027 to 2029 includes the development of a «smart policy portfolio» along with strategic hydrogen projects, including regulatory and technology development issues.

The draft Roadmap for the use of hydrogen in Ukraine in the field of road transport [53] includes an analysis of the best international practices and plans for the use of hydrogen in the road transport sector with a focus on urban public transport.

In general, the adaptation of the concepts enshrined in the above documents can create a positive dynamics of transformation. General vectors of changes planned by government agencies and identified from different programs are grouped in Fig. 4.

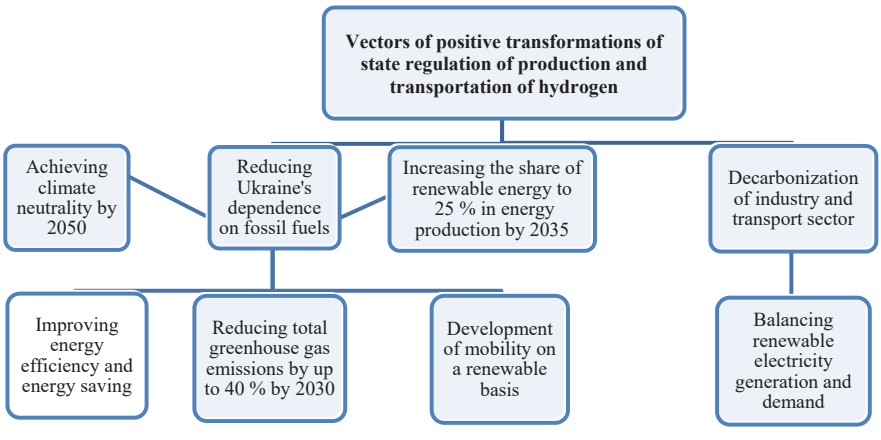


Fig. 4. Prospective positive transformations of the legislation of Ukraine on the way of adaptation of the European concepts of «green» hydrogen

At the same time, despite the ambitious goals of Ukraine in the direction of approaching 67 European standards in the field of state regulation of the production and transportation of hydrogen, there is no state regulation on the territory of the state. The innovations proposed in the draft Roadmaps remain declarative and not adapted to the realities of the present. Therefore, the problem of even developing a basic legal framework for the constancy of approaches to the use of hydrogen is urgent.

At the same time, the real state of hydrogen production and transportation in Ukraine after February 24, 2022 deserves attention. Moreover, the full-scale invasion of the Russian Federation on the territory of the state affected both the stability of the state as a whole and the planning for the implementation of reform measures in the short term. The consequences of the global economy caused by the war in Ukraine, in turn, increased the demand for green hydrogen in the Middle East and North Africa region. This energy source is becoming popular among European countries that are planning to implement a clean energy transition soon, as it can help decarbonize certain key sectors such as transport, shipping, aviation and manufacturing. Green hydrogen can be used as a fuel in these industries. Hydrogen will dominate the market due to the aggressive policy of Russia and the refusal of many countries from fossil fuels.

Political developments, together with commercial interests, suggest that Ukraine has the potential to export hydrogen produced from renewable sources and nuclear power before the end of the decade. Ukraine has one of the

largest gas transmission systems in the world, which gives it an advantage for future hydrogen supplies to Europe. But its network needs a lot of capital investment, as it mostly comes from Soviet times and is being destroyed by air strikes. However, Ukraine still has significant water resources and above average solar and wind potential. These are the prerequisites for green hydrogen, or hydrogen produced from renewable energy sources.

It can be stated that significant commercial interests of the EU will be needed to turn the hydrogen potential into real export capacities. In addition, the possibility of a major energy crisis is real, while hydrogen will take decades to displace natural gas. The intensification of hydrogen introduction processes can be facilitated by domestic business representatives, most of whose industrial capacities are concentrated in the eastern part of the country, where shelling and destruction continue. Right now, there is no incentive for Ukrainian companies to invest in hydrogen for domestic use, as it would be too expensive for Ukrainian consumers. However, it makes sense for other European countries to increase hydrogen supplies.

A further vector for scientific research may be the actualization of future results of state regulation regarding the introduction of hydrogen production and transportation in Ukraine in the post-war period. The possible implementation of the relevant EU experience in Ukrainian legislation will be an important basis for the next scientific research.

## 6. Discussion of the results of the study of innovations in the legal regulation of the decarbonization of Ukraine in the light of scientific discussions

The results of the study substantiated that countries that plan to produce and use clean hydrogen should give priority to detailed analysis and planning of economic transformations. The levels of hydrogen purity that can be implemented are shown in Fig. 2, allow to adjust the initial legislative innovations.

Based on the results of scientific research, it can be stated that the state policy of European states should support the development of sustainable and renewable technologies, such as hydrogen, at the initial stage. As a result of political decisions, new projects and investments can be initiated that can raise awareness of hydrogen security. In turn, the effectiveness of legalized innovations should be properly ensured by the state. In contrast to the classical mechanisms for the implementation of legal norms, in the relevant legal relations, basic tax benefits for business entities should be fixed. Such a state approach to regulating the circulation of hydrogen will increase the attractiveness of the entry of new technologies into business.

To quickly reduce emissions through the introduction of clean hydrogen, governments must adopt market-based policies and production standards. Local, regional and national governments interested in developing green hydrogen should prioritize building the necessary infrastructure. It is substantiated that governments involved in the introduction of environmentally friendly hydrogen should increase investment in innovation, including research and experimental development. Consequently, bureaucratic archaisms and lack of proper funding may become obstacles to the proposed changes. In turn, the developers of legal regulation should qualitatively take into account the advantages of «green» hydrogen in the process of standard setting and practical aspects of its production. Variable methods of hydrogen storage and transportation (Fig. 3) should not be ignored by legislators in order to further effectively implement the declared norms in practice.

The conducted research gives grounds to assert that the transportation and distribution of hydrogen is closely connected with the existing natural gas network. At the same time, ensuring the innovative implementation of hydrogen transportation technologies is largely limited by national permitting regulations. The scientists support the position of the authors and emphasize that legal ways should be considered at the national level to support the development of the gas pipeline and thus provide more opportunities for the development of the electricity-gas interconnection [5]. However, the lack of specific rules will hinder industrial operations in many ways (impact on time, cost, etc.). Therefore, governments must support coordination, regulation, and standardization to bring hydrogen energy systems to market.

Policy action is needed for the hydrogen industry, based on the decarbonization approach and the latest paradigm in policy development, combining bottom-up and top-down approaches [11]. It has been shown that, in this regard, focusing on tailored policy mixes can be a key way to address socio-technical needs and in turn catalyze the transition to a green hydrogen economy. In addition, in the next few years, an important component for government regulation will be the extent to which new investments in infrastructure should be ready for hydrogen [54]. In this context, noteworthy is the position of scientists that new gas-fired power plants should be designed with the possibility of a rapid transition to hydrogen in the future [54]. A detailed feasibility study of the growth in demand for hydrogen for new industrial and transport applications is also needed, even though the use of petrochemicals is declining with increasing decarbonization [55].

Thus, international policy initiatives are needed to support open hydrogen value chains, technology exchange, public-private partnerships in research and development, and joint development of research funding schemes. It is also necessary to create international hubs and centers of excellence, as they can help reduce costs and realize synergies [55] and rapid adaptation of legalized changes.

It can be stated that one of the main problems of the subject under study is how safe and reliable the hydrogen production and distribution network will be in the hydrogen economy of Ukraine. Problems with leakage, thermal effects, crackling and fire will be of even greater concern when hydrogen is transported over long distances within national borders. Consequently, this area requires more and more careful study in the next few years and strengthening the quality of state regulation [4]. Scientists emphasize that, in addition, given the technology of hydrogen production, the most technologically ready «green» technology for the production of hydrogen is the electrolysis of water from various energy sources. It is very important to conduct further research on improving the process of hydrogen production from water electrolysis in order to reduce costs.

The development of infrastructure, production and marketing chains should be focused on the potential of use and the differences existing in this context in specific EU countries [9]. This, according to scientists, opens up the potential of a new European division of labor within the framework of

a common hydrogen network, both in terms of production and consumption. This highlights the need for interstate cooperation when planning the long-term prospects for the European hydrogen infrastructure. In this sense, Ukraine's national plans for the medium term should be agreed on the basis of pan-European consultations under the auspices of the EU's hydrogen strategy.

Important proposed solutions for the development of hydrogen energy in Ukraine should be:

– development of an additional legal, regulatory and technical framework for renewable energy, taking into account the characteristics of hydrogen energy;

– implementation of the components of the state policy of economic stimulation of hydrogen energy, which is based on the introduction of a system of benefits for producers and consumers of energy;

– definition of financing mechanisms.

Also, the proposed by the authors in Fig. 4 promising positive transformations of Ukrainian legislation on the way to adapting the European concepts of «green» hydrogen. Scientists support the position of the authors. When introducing developments in the field of hydrogen energy based on renewable energy sources, it will contribute to the creation of its own application base. In turn, this will lead to an increase in the level of scientific research and the formation of a positive image for potential investors and consumers [10].

At present, it seems necessary to organize information support and an educational system for the formation of technical and environmental-energy consciousness of the population using all media [10]. Among the priority areas for the development of the regulatory framework in Ukraine, attention should be paid to the creation of safety standards for the use of hydrogen in various technical processes. Outside of justified criticism of «archaisms» and gaps in the legal regulation of European states, lawyers focused on the advisability of reforming the permitting base for the use of hydrogen in economic activity. Innovations are proposed in the field of laying the foundations of the «green» hydrogen market (guarantees of the origin of electricity and hydrogen, a system to support the implementation of «green» hydrogen projects) [12]. At the same time, the proposed solutions cannot be fully implemented in the absence of a mechanism for effectively ensuring the implementation of the declared norms. In turn, the shortcomings of the proposed reasonable expectations of the updated legal regulation of the decarbonization of Ukraine may be the realities of the military conflict on the territory of the state, which will interfere with the implementation of the law. However, despite the difficulties in legalizing the proposed innovations, the results of the study will become an effective basic tool for restoring the Ukrainian economy in the post-war period and quickly entering the European market.

## 7. Conclusions

1. Concerns about climate change are growing around the world, so more governments, organizations and institutions are adopting new environmental initiatives. Concerns about the long-term sustainability of fossil fuel use have drawn the attention of countries to the need to develop and invest in low-carbon technologies to maintain global security. The most attractive fuel option recently proposed for the implementation of the «green» economy is hydrogen. Factors such as pollution levels, technical issues and energy requirements vary depending on the sources used. Environmental sustainability during the life cycle remains one of the key requirements when choosing hydrogen production mechanisms. Hydrogen energy is very versatile, as it can be used in gaseous or liquid form, converted into electricity or fuel, and there are many ways to produce it from methane, gasoline, biomass, coal or water.

2. The negative consequences of the armed anger of the Russian Federation led to the rapid implementation of the REPowerEU course. The priority actions of the European Union are to rapidly reduce dependence on Russian fossil fuels by joining forces to achieve a more sustainable energy system and a true Energy Union. It is now recognized that cross-border cooperation is needed to deploy a hydrogen infrastructure to produce, import and transport 20 million tons of hydrogen by 2030 in Europe. At the same time, the transition to an actual hydrogen economy requires decisive action by governments in research, development and implementation of hydrogen technologies. Appropriate changes in the regulatory framework of states can provide significant assistance in achieving the necessary technological breakthroughs. At present, the main challenge for the European Union in the field of the hydrogen economy is to provide the right incentives and choose the best legal and regulatory framework to implement the necessary changes in a cost-effective way that will benefit EU citizens. Modern innovations in the legislation of the EU and member states testify to the desire to develop a hydrogen energy system on the way to a carbon-neutral society. State regulation of the production and transportation of hydrogen in the EU should be subject to:

1) the latest technological developments;

2) cross-border innovation partnership;

3) technically efficient methods of hydrogen production and storage;

4) implementation of the declared long-term sustainable development goals.

3. Ukraine has a high potential for renewable energy sources, which can become a prerequisite for the production of «green» hydrogen not only for its own needs, but also for its delivery to the European Union. However, in Ukraine there are no economic conditions and infrastructure for realizing such a prospect. State regulation remais fragmented and declarative. For Ukraine, it is expedient to introduce timely regulatory and technical adjustments that will produce an increase in Ukraine's potential in the direction of decarbonization. The introduction of a high-quality legal framework will allow Ukraine to acquire a qualitatively new partner status in the supply of «green» hydrogen to the territory of the European Union. At the same time, the war on the territory of the state, the fuel crisis, difficulties with energy carriers and the growing demand for alternative energy sources are accelerating the introduction of hydrogen technologies and coordination activities to establish rapid transportation of hydrogen to Ukraine. However, in the medium and long term, climate goals and energy independence must be accelerated through tough legislative action on the territory of Ukraine and other European states.

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