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Assessment of the Guaranteed Origin of Electricity Used for Green Hydrogen Production in an Integrated Energy System

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Abstract. The formation of integrated energy systems is a result of the decentralization of power generation, the expansion and increasing capacity of renewable energy sources, and the implementation of Smart Grid technologies. A distinctive feature of such systems is the integrated use of electricity, gas, and heat within a single infrastructure with intelligent control. In these systems, electricity generated by various types of power plants, including both renewable and conventional sources, is transmitted through a common network to consumers. One of the promising consumers in integrated energy systems is an electrolyzer, which is used for hydrogen production and can also participate in power balancing within such systems. In the context of decarbonization, it is important to determine whether the electricity consumed by the electrolyzer meets the criteria of low-carbon energy, as this directly affects the classification of the produced hydrogen as "green".

This paper proposes a mathematical model for determining the guaranteed origin of electricity consumed by an electrolyzer in an integrated energy system. The model is based on a matrix method for determining power flows in the branches of an electrical network and on the use of current distribution coefficients in network branches originating from nodes with renewable energy sources and node voltages. This approach makes it possible to determine the contribution of each generation node, particularly renewable energy sources, to the supply of a specific consumer. The proposed method enables the quantitative assessment of the share of renewable electricity used in hydrogen production and provides a physically justified basis for confirming its "green" status.

Key words. Integrated energy system, guarantees of origin of electricity, green hydrogen.

1. Introduction

Addressing the challenges of climate change and global warming requires active measures to reduce CO_2 emissions in both the industrial and energy sectors. The decarbonization of the energy sector involves a transition from fossil fuels with a high carbon footprint to low-carbon energy sources (LCES), such as solar, wind, and hydropower, as well as nuclear energy, including that generated by modern small modular reactors. At the same time, the development of hydrogen technologies is an important component of the energy transition, as it enables the integration of the electricity, gas supply, and heat supply sectors. Hydrogen produced through water electrolysis using low-carbon electricity is considered a universal energy carrier and a means of long-term energy storage (Power-to-Gas).

Despite the long-term development of decarbonization policies, a number of technical and market challenges remain unresolved. Governments of developed countries are implementing mechanisms to support low-carbon technologies, including guarantees of origin (GO), power purchase agreements (PPA), the Carbon Border Adjustment Mechanism (CBAM), and other instruments. For companies operating under ESG (Environmental, Social, Governance) standards, confirmation of low-carbon electricity consumption is a necessary condition for maintaining competitiveness and minimizing additional tax burdens when exporting products to the European Union. In this context, determining the origin of electricity within the consumer's energy mix becomes particularly relevant, especially for the production of "green" hydrogen [1, 2].

The gradual transition to decentralized generation has led to the development of various distributed energy sources within individual territorial communities, resulting in the formation of integrated energy systems (IES). An IES represents a new type of energy system based on Smart Grid technologies and intelligent operational control, enabling the integrated use of electricity, heat, natural gas, and hydrogen within a unified infrastructure. In such systems, electrolyzer units not only perform the function of hydrogen production but also participate in power balancing to compensate for the variability of renewable energy generation.

In the context of decarbonization, enterprises operating within an IES require tools for the quantitative determination of the share of power obtained from low-carbon sources while accounting for electricity transmission losses.

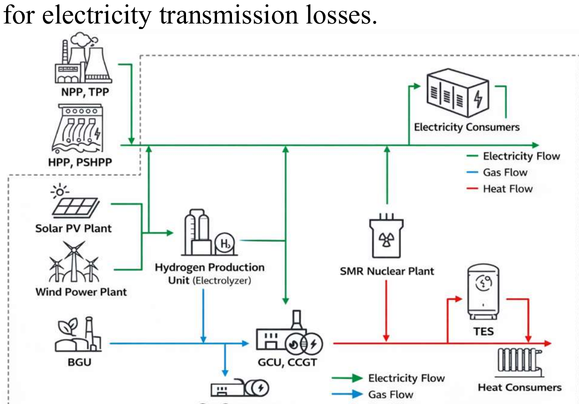

Fig. 1. Structure of an integrated energy system with hydrogen production

The proposed approach makes it possible to evaluate the contribution of low-carbon energy sources to the supply of a specific consumer, particularly an electrolyzer, and to provide physically justified confirmation of the origin of electricity. The calculated losses can also be used in market models, particularly for compensation calculations and for developing economically efficient mechanisms to support low-carbon hydrogen production [3].The implementation of the proposed method will contribute to the 5D transformation of Ukraine's energy sector (decarbonization, digitalization, decentralization, democratization, and deregulation), increase transparency in determining the origin of electricity, and support the development of the low-carbon hydrogen market [4, 5].

2. Hydrogen Classification

Fig. 2 presents the classification of hydrogen according to the color spectrum depending on the production technology and the associated level of carbon dioxide emissions. This classification is widely used in energy research to indicate the primary energy source and the environmental characteristics of hydrogen production [6].

Green hydrogen is produced through water electrolysis using electricity generated from renewable energy sources, including solar, wind, and hydropower plants. In this process, direct CO_2 emissions are practically absent, and the by-products are oxygen and water.

Blue hydrogen is produced from natural gas through steam methane reforming (SMR) or autothermal reforming with the use of carbon capture and storage technologies (CCUS). Compared to conventional hydrogen production, CO_2 emissions are reduced but not completely eliminated.

Gray hydrogen is obtained from natural gas through steam methane reforming without the use of carbon capture technologies, which results in significant CO_2 emissions into the atmosphere.

Pink hydrogen is produced by water electrolysis using electricity generated by nuclear power plants and is characterized by a low level of carbon emissions.

Black hydrogen is produced through coal gasification, which is associated with very high CO_2 emissions.

Turquoise hydrogen is produced through methane pyrolysis, in which methane is split into hydrogen and solid carbon, allowing a reduction of the carbon footprint compared to traditional technologies.

White hydrogen refers to naturally occurring hydrogen found in underground geological formations that can be extracted directly from subsurface resources.

The presented classification makes it possible to systematize hydrogen production technologies according to the primary energy source and their impact on the level of decarbonization of the energy system, which is important from the perspective of consumers interested in environmentally friendly production.

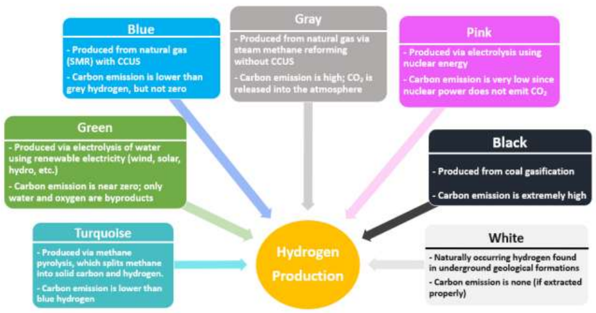

Fig. 2. Hydrogen classification

3. Concept of the Guaranteed Origin of Electricity

Algorithm for determining power and energy losses in specified branches of an electric grid

In Fig. 2, the algorithm for determining the share of power generated by LCRES and delivered to a specified electricity consumer is presented. The approach embedded in the algorithm is based on identifying the power flows in the branches of the electric grid that are incident to the nodes containing the predefined list of electricity consumers supplied from LCRES. Directly at the node, using the power balance, the power consumed by each consumer specifically oriented toward consuming electricity from a particular LCRES is calculated with consideration of the physical processes occurring in the electric grid. Thus, it becomes possible to assess the amount of load coverage for a given consumer by LCRES that supply energy to the power system during a controlled time period *T*. The input data for the calculation include the parameters of the electric grid, node loads specified either as power values or load profiles, as well as the generation profiles of the low-carbon energy sources present in the grid [6-8].

To convert the consumer's power demand into the amount of electricity consumed, methods of average or maximum loads are used. Depending on the selected method, either the average load $\dot{S}_{av}$ or the maximum load $\dot{S}_{max}$ of the consumer over period *T* is specified. A more accurate approach is to use a forecasted hourly consumption profile for the next day together with actual consumption data obtained from the automated control system (ACS). In the first case, the forecasted amount of electricity planned for consumption from LCRES is determined. In the second case, the actual amount of electricity consumed from LCRES is calculated.

These data are then transferred to the registry of guarantees of origin, taking into account the volume of guaranteed load coverage of the consumer with energy from low-carbon energy sources. Depending on the requirements and the technical capabilities of the metering system, the program is launched either hourly or according to generation and consumption schedules within the electric grid.

The array of node voltages required for the calculations can be obtained in two ways: either as the result of steady-state grid operation analysis or from ACS measurements. If hourly forecasted values of LCRES generation and consumption are used, the voltages are determined from steady-state calculations or, when the required accuracy allows, from average statistical data. If the actual values are determined, the input data are the voltage measurements provided by the ACS [9-12].

After forming the array of node voltages, the incidence $\mathbf{M}_{\Sigma}$ matrix and the matrix of coefficients for the distribution of node-injected currents in the branches of the electric grid $\dot{\mathbf{C}}$ are generated. Subsequently, the matrix of power-distribution coefficients for the nodes across the branches of the electric grid $\dot{\mathbf{D}}$ is calculated; it consists of the $\dot{\mathbf{D}}_i$ row . Using matrix $\dot{\mathbf{D}}$, the portions of the total LCRES power $\dot{\mathbf{S}}_{b\,LCRES}$ that flow through the branches of the grid are determined. Summing the LCRES power flows $\dot{S}_{b\,LCRES}$ in the branches incident to the *j*-th nodes with controlled consumption from LCRES makes it possible to determine the guaranteed volumes of electricity originating from LCRES for these consumers. Such nodes may be of two types. If a node is terminal that is, only one branch carrying LCRES power $\dot{S}_{LCRES\,j}$ reaches it hen this power represents the amount of electricity originating from LCRES for the given consumer. The power $\dot{\mathbf{S}}_{LCRES\,j}$ may be determined as the sum of the power flows from nuclear power plants $\dot{\mathbf{S}}_{NPP\,j}$ and renewable sources $\dot{\mathbf{S}}_{RES\,j}$ to the j-th node. In certain cases, depending on the topology, operating mode of the electric grid, and the presence of distributed energy resources, the power $\dot{\mathbf{S}}_{LCRES\,j}$ may be determined by only a single component – either from nuclear power plants or from renewable energy sources, respectively. If the node is an intermediate node, the power $\dot{S}_{LCRES\,j}$ is determined from the power balance at the *j*-th node.

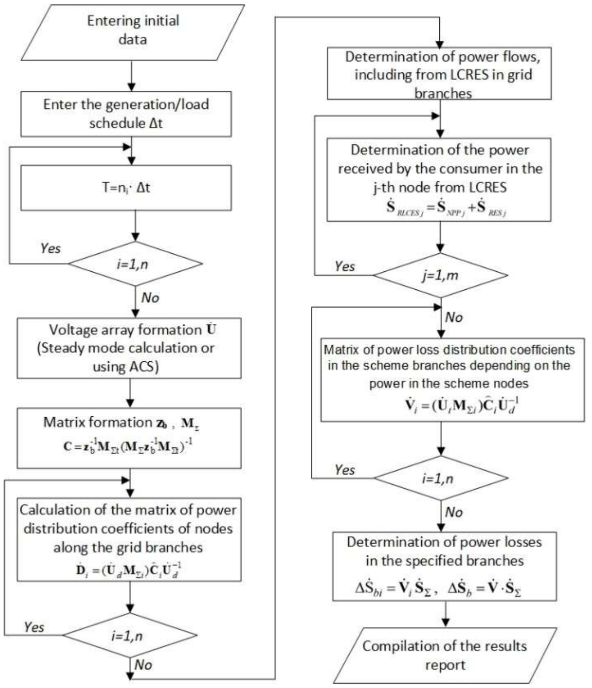

Fig 3. Algorithm for determining the amount of electricity consumed that originates from low-carbon and renewable energy sources.

4. Application of the Method

To demonstrate the effectiveness of the method for determining the origin of electricity consumed from renewable energy sources, a fragment of a 110 kV network shown in Fig. 4 is considered. The parameters of the network model, namely generation and load at the nodes, as well as branch impedances, are presented in Table 1.

A hydrogen hub based on electrolyzers (Electrolyzer-based Hydrogen Hub – EHH) is connected to node 5, which consumes 25 MW from the network for hydrogen production. Node 1 is considered as the slack bus, while two photovoltaic power plants are connected to nodes 5 and 6, respectively. A reference load-flow calculation for the steady-state operating conditions corresponding to the maximum PV generation (at 13:00) was performed using the PowerFactory 15.1 software package. The node voltages obtained from the computer simulation are presented in Table 1.

Table I – Information about Network Nodes

Branch No.	Impedance, Ω	Node No.	P, MW	Q, Mvar	U, kV	Phase, deg
1	9+8,1i	1	-51,8	-44,7	114,95	0
2	4,5+4,05i	2	35	19	112,89	-0,03
3	4,5+4,05i	3	20	12	111,85	-0,01
4	11,25+10,125i	4	-15	0	112,81	0,24
5	18+16,32i	5	25	15	109,1	0,07
6	13,5+12,15i	6	-15	0	111,79	0,6
7	15,75+14,2i	-	-	-	-	-

According to the proposed method, the calculated node voltage values are substituted to compute the power distribution coefficient matrix (1):

$$\begin{array}{cccccccc} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \\ \dot{\mathbf{D}} = & 0{,}165+7{,}6i\cdot10^{-5} & 0{,}668-3{,}6i\cdot10^{-5} & 0{,}329-0{,}001i & 0{,}553-0{,}001i & 0{,}444-0{,}005i & 1 \\ & 0{,}166+1{,}8i\cdot10^{-5} & -0{,}335+8{,}1i\cdot10^{-5} & -0{,}668+0{,}003i & -0{,}476+0{,}001i & -0{,}561+0{,}006i & \mathbf{2} \\ & 0{,}834-1{,}8i\cdot10^{-5} & 0{,}335-8{,}1i\cdot10^{-5} & 0{,}668-0{,}003i & 0{,}476-0{,}001i & 0{,}561-0{,}006i & \mathbf{3} \\ & -0{,}133-1{,}8i\cdot10^{-5} & 0{,}268-5{,}8i\cdot10^{-5} & -0{,}266+0{,}001i & 0{,}065+3{,}1i\cdot10^{-4} & -0{,}09+0{,}001i & \mathbf{4} \\ & 0{,}031+9{,}8i\cdot10^{-5} & -0{,}062-1{,}7i\cdot10^{-4} & 0{,}062-9{,}2i\cdot10^{-5} & 0{,}603+0{,}001i & 0{,}346-0{,}003i & \mathbf{5} \\ & -0{,}031-9{,}8i\cdot10^{-4} & 0{,}062+1{,}7i\cdot10^{-4} & -0{,}062+9{,}2i\cdot10^{-5} & 0{,}397-0{,}001i & -0{,}346+0{,}003i & \mathbf{6} \\ & -0{,}032-3{,}9i\cdot10^{-5} & 0{,}0647+7{,}7i\cdot10^{-4} & -0{,}063-4{,}9i\cdot10^{-4} & 0{,}406+0{,}003i & 0{,}646-2{,}6i\cdot10^{-4} & \mathbf{7} \end{array} \quad (1)$$

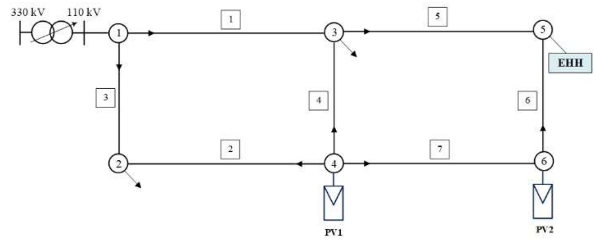

Fig. 4. Electrical network scheme

By multiplying the matrix of power distribution coefficients of the nodes by the column vector of loads and generation at the nodes, the matrix of power distribution along the branches of the electrical network is obtained, including the contribution from renewable energy sources. The values of the elements in the columns of this matrix represent the distribution of power flows along the branches of the network originating from renewable energy sources. This makes it possible, through calculation, to determine what share of "green" electricity was consumed by a specific consumer. For example, in the case of the consumption of the Electrolyzer-based Hydrogen Hub (EHH), it can be determined that 12.24 MW of electricity from renewable energy sources was used for the production of green hydrogen, while the remaining part was supplied from the power system.

Furthermore, having the matrix of power distribution along the branches of the electrical network, it is also possible to determine the matrix of power losses caused, among other factors, by the power flows from renewable energy sources (2).

$$\begin{array}{cccccccc} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \\ \dot{\mathbf{S}}_{в} = & 5{,}76+3{,}13i & 13{,}36+8{,}01i & -4{,}94+0{,}02i & 13{,}84+6{,}63i & -6{,}66+0{,}07i & \mathbf{1} \\ & 5{,}81+3{,}16i & -6{,}71-4{,}02i & 10{,}02-0{,}05i & -11{,}92-5{,}69i & 8{,}42-0{,}09i & \mathbf{2} \\ & 29{,}19+15{,}84i & 6{,}71+4{,}02i & -10{,}02+0{,}05i & 11{,}92+5{,}69i & -8{,}42+0{,}09i & \mathbf{3} \\ & -4{,}65-2{,}53i & 5{,}37+3{,}22i & 3{,}99-0{,}02i & 1{,}62+0{,}79i & 1{,}34-0{,}02i & \mathbf{4} \\ & 1{,}08+0{,}59i & -1{,}24-0{,}75i & -0{,}93+1{,}39\cdot10^{-3}i & 15{,}07+7{,}26i & -5{,}19+0{,}04i & \mathbf{5} \\ & -1{,}08-0{,}59i & 1{,}24+0{,}75i & 0{,}93-1{,}39\cdot10^{-3}i & 9{,}93+4{,}74i & 5{,}19-0{,}04i & \mathbf{6} \\ & -1{,}1+0{,}61i & 1{,}27+0{,}78i & 0{,}95+7{,}38\cdot10^{-3}i & 10{,}12+4{,}96i & -9{,}68+4{,}03i\cdot10^{-3} & \mathbf{7} \end{array} \quad (2)$$

The values of the elements in the columns of the matrix represent the distribution of power flows along the branches of the network originating from renewable energy sources (RES). This makes it possible, through calculations, to determine the share of "green" electricity consumed by a specific consumer. For example, in the case of the Electrolyzer-based Hydrogen Hub (EHH), it can be determined that 12.24 MW of electricity from RES was used for green hydrogen production, while the remaining part was supplied from the electric power system.

Furthermore, having the matrix of power distribution along the branches of the electrical network, it is also possible to determine the matrix of power losses caused, among other factors, by power flows from renewable energy sources (3):

$$\Delta \dot{\mathbf{S}}_{в} = \begin{array}{c|ccccc|c} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \\ & -0,16-0,09i & -0,37-0,22i & 0,14 & 0,38-0,19i & 0,18 & \mathbf{1} \\ & 0,02-0,03i & -0,02+0,03i & 0,01-0,05i & -0,04+0,05i & 0,01-0,04i & \mathbf{2} \\ & -0,52-0,3i & -0,12-0,08i & 0,18 & -0,21-0,11i & 0,15 & \mathbf{3} \\ & 0,03+0,04i & -0,03-0,05i & -0,03-0,02i & -0,01-0,01i & -0,01-0,01i & \mathbf{4} \\ & -0,03-0,01i & 0,03+0,02i & 0,02 & -0,39-0,16i & 0,13-0,01i & \mathbf{5} \\ & 0,02+0,02i & -0,02-0,03i & -0,02-0,01i & -0,2-0,21i & -0,13-0,05i & \mathbf{6} \\ & 0,01 & -0,02i & -0,01+0,01i & -0,12+0,02i & 0,09-0,06i & \mathbf{7} \end{array} \quad (3)$$

The total active power losses calculated using the matrix method amount to 1.828 MW (including 1.1 MW of losses caused by RES power flows). According to the steady-state power flow calculation performed using the PowerFactory 15.1 software package, the total losses are 1.83 MW, which confirms the adequacy of the proposed method.

Conclusion

The formation of integrated energy systems represents a natural stage in the development of the energy sector under the need to address the challenges of the 5D transformation, namely the decentralization of generation, decarbonization of the economy, digitalization of energy management processes, as well as the democratization and deregulation of energy markets. The integration of electricity, heat, and gas systems based on Smart Grid technologies creates the prerequisites for increasing the flexibility and resilience of energy supply. However, it simultaneously complicates the determination of the origin of consumed electricity for consumers seeking to operate in an environmentally responsible manner.

This paper proposes a mathematical model for determining the guaranteed origin of electricity consumed by an electrolyzer in an integrated energy system. The model is based on a matrix method for the distribution of power flows in the branches of an electrical network, taking into account the network topology, node voltages, and electricity losses. This approach makes it possible to quantitatively assess the contribution of renewable energy sources to the supply of an electrolyzer unit and to establish a physically justified criterion for determining the “green” status of the produced hydrogen.

Unlike existing guarantee-of-origin mechanisms, which are mainly based on commercial principles, the proposed approach takes into account the real physical processes of power distribution in the electric power system. The obtained results can be used in the development of digital monitoring tools, in the improvement of market mechanisms supporting decarbonization, and in the creation of a transparent certification system for low-carbon hydrogen within integrated energy systems.

In future research, further efforts will be focused on expanding the proposed approach and developing a comprehensive indicator for assessing the efficiency of integrated energy systems. Particular attention will be paid to the diversification of energy sources and technologies within such systems, as well as to the decomposition of energy flows and subsystems in order to improve the evaluation of their operational performance and sustainability.

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