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Energy community in the task determining the origin of electricity from low-carbon energy sources for consumers

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Abstract. In the paper implementation in Ukraine of the 5Ds strategy is discussed. The Energy Community is one of the approaches to implementing the 5Ds strategy. Citizens want to use electricity produced from low-carbon energy sources. The paper focuses on the possibility of applying a method for calculating individual components of electricity flows in the branches of an electric power grid caused by generation and consumption in the nodes. In particular, it is about estimating the portion of electricity of a particular consumer that it receives from low-carbon energy sources (LCES). The method is based on methods and algorithms for calculating steady-state modes of power grids. The method is based on a mathematical model for determining the components of power flows in the branches of an electrical grid, which uses the coefficients of current distribution in the branches of the circuit from nodes with generation sources and nodal voltages. Since LCES, including renewable sources of energy (RSE) plants and nuclear power plants in electric power systems (EPS), use general power grids to transmit the electricity it generates, determining their share of power in the flows allows taking into account the impact of different sources of generation on the parameters of the EPS mode. In this paper, the steady-state mode of a 14-node circuit with different energy sources, including renewable energy sources, is calculated. In particular, by calculations using the method of guaranteed electricity origin, power flows in the branches of the electrical circuit and power losses in them were determined. The results of computer modelling in the Power Factory software complex are commensurate with the results of calculations, which confirms the adequacy of the method.

Key words. origin of electricity, energy community, mathematical model, computer modelling, low-carbon energy sources, renewable sources of energy, matrix of LCES power distribution coefficients.

1. Introduction

Decarbonization, digitalisation, decentralization, democratization, deregulation (5Ds) policies are an important part of global efforts to combat climate change and reduce greenhouse gas emissions, energy safety and energy independency [1-3]. Decarbonization involves reducing dependence on carbon-based energy sources (coal, oil, gas) and transition to renewable energy sources (wind, solar, hydropower, etc.) in all sectors of production [4-6]. As noted in the IEA Net Zero by 2050 report [7], hydropower and nuclear power are the two largest sources of low-carbon electricity that currently provide an important basis for the energy transition. It is also important to pay attention to the European Green Deal [8], a strategic plan of the European Union (EU) focused on achieving climate neutrality by 2050. Among the main goals and measures of the Green Deal is climate neutrality, namely, reducing greenhouse gas emissions to zero by 2050. In particular, it is about reducing emissions in all sectors of the economy, including energy, transport, industry and agriculture. Special attention is also devoted to the energy transition, which aims to increase the share of renewable energy sources and improve energy efficiency. This includes the development of solar, wind and other types of green energy. Ukraine has signed and ratified the Paris Agreement, but achieving the goals of decarbonizing the electricity sector requires significant financial investments. Without substantial investments in the modernization of the energy sector, including the development of renewable energy sources and reduction of dependence on fossil fuels, it is extremely difficult to realize the commitments. For the stable functioning of the carbon-free energy system of Ukraine, as noted in [9], it is necessary to create powerful seasonal energy storage systems with a total energy intensity of 6 to 15% of the annual volume of electricity supplied. Various instruments are used around the world to stimulate investment in renewable energy development. In particular, to meet the goals of sustainable development, companies purchase Guarantees of Origin (GO [10-15]) or enter into PPAs (Power Purchase Agreements [16, 17]). In this way, producers seek to reduce their carbon footprint and prove that the energy they consume comes from renewable sources. This, in turn, allows manufacturers to produce products with green labeling and/or improve the company's image in the eyes of customers, investor s, and partners. It is also worth noting that PPA contracts often allow companies to lock in energy prices for a long period of time, which can protect them from fluctuations in the energy market and provide long-term financial benefits. The task of determining the origin of electricity, especially when the source is located at a distance from the manufacturer and generates to the general electricity grid rather than directly to the consumer (physical PPA), is complex, as it is necessary to know the costs of transmission of electricity from renewable energy to distribution system operators, and to determine what share of the energy mix received by the consumer is produced by renewable energy sources.

Also, citizens are interesting in use electricity, which are produced by renewable energy sources or low-carbon energy sources. It is confirmed by increasing number of created energy communities in all worlds. Energy communities are associations of citizens, organizations or businesses that jointly own and manage renewable energy projects. An energy community can be created based on industrial parks, hospitals, schools and educational institutions, condominiums, public organizations, etc [18-20].

Members of such a community create a legal entity to produce electricity, including from renewable sources, and can engage in distribution, supply, consumption, aggregation, energy storage, provision of energy efficiency services or electric vehicle charging services, or provide other energy services to its members. Currently, the status of “green” energy communities is not clearly defined in the national legislation of Ukraine, which hinders their development. That is why it is important to consolidate the concept of creating energy communities in local strategic and program documents. The Vinnytsia community is one of the first to fully realize the importance of the "green" transition and identified the need to transform local documents in accordance with global trends. Thus, in 2022, the Vinnitsya town in Ukraine was the first to proclaim the "Green Course of Vinnytsia", the basis for the implementation of which are the principles and principles of the EU initiative "European Green Deal", adopted in 2019. Achieving climate neutrality lies at the heart of the Vinnytsia Green Course and is its central element. Decarbonization of the energy system, the transition to renewable energy sources (RES), and support for energy efficiency are critically important for achieving the climate goals. At the same time, the war in Ukraine, systematic shelling of the energy system form the need for decentralization of the energy system, the transition to environmentally efficient renewable energy sources. All this can be achieved by implementing a system of measures, including the formation of energy communities, the activities of which will help accelerate and scale local initiatives of citizens to implement distributed renewable energy generation projects and create “green” jobs in Ukraine. Nowadays, develop specific solutions and a roadmap for decarbonisation of region are obligatory for energysafety. The war in Ukraine, systematic shellings of the energy system create the need for decentralization of the energy system, transition to environmentally efficient renewable energy sources. All this can be achieved by implementing a system of measures, including the formation of energy communities, the activities of which will help accelerate and scale local initiatives of citizens to implement distributed renewable energy generation projects and create “green” jobs in the Vinnytsia region.

The article aims is determining of the electricity amount of consumer receives from low-carbon energy sources to confirm its origin, allowing manufacturers to produce green-labelled products and citizens consume of RES produced electricity.

2. Literature Review

Determining the origin of electricity, namely tracking the flows of active and reactive power, is necessary from the point of view of the producer and consumer (including active power) to achieve a fair electricity market, as the costs of operating, using and maintaining the system must be distributed properly. In particular, flow tracing was presented by Bialek as a loss allocation scheme based on solving linear equations [21], and in parallel by Kirschen as an analytical tool that uses an iterative approach based on graphs [22]. The availability of ring circuits significantly complicates the algorithms for calculating power flows, especially in grids with a high density of connections of different types of dispersed energy sources, including wind and solar power plants, whose operation mode depends on weather conditions. This necessitates the improvement of existing methods, especially given that responsible producers want to know what share of electricity they receive from RSE. For example, paper [23] describes a method for tracking the power flow in the power grid and distributing the use of line capacity among the relevant sources or consumers using a diffusion-like process, taking into account the structure of the grid and the connection points of generation sources. The methods described above were used to create the Electricity Map [23]. The advantage of the Electricity Map is its advanced analytical information, in particular, it provides access to a range of data on electricity, carbon intensity of each type of power plant, electricity consumption and the share of electricity generated from low-carbon energy sources for each country. However, it is possible to obtain information on cross-border flows between countries. The task of determining the origin of electricity in smaller-scale systems, for example, within a single territorial community, or, for example, an energy cooperative or community, is relevant. In [24], a method for determining the origin of electricity is described, which is based on a

mathematical model for determining the components of electricity flows in the branches of an electrical network circuit, which uses the coefficients of current distribution in the branches of the circuit from nodes with generation sources and nodal voltages. The methodology proposed in this article formed the basis of the studies described further in the article.

Algorithm for calculation of the portion of electricity consumption of a given consumer that is from low-carbon energy sources

The main idea of the method for determining the portion of power flows in power grids from a set of LCES to certain load nodes, shown in [25], is to first determine the value of the total power at the begin and end of each branch of the circuit using the formulas:

$$\dot{S}_{br} = \sqrt{3}\,\dot{U}_d\,\mathbf{M}_{\Sigma}\,\hat{I}_d\,, \qquad (1)$$

where $\dot{S}_b$ is a power matrix where the columns represent the power of the begin and end of the power grid branches. $\dot{U}_d$ is the diagonal matrix of voltages in the nodes, including the balancing nodes; $\mathbf{M}_{\Sigma}$ matrix of branch connections in nodes, including balancing nodes; $\hat{I}_d$ diagonal matrix of currents in the branches of the circuit (hereinafter, the sign $\widehat{\ }$ means that the matrix or vector is conjugate).

To determine the portion of power transferred from the LCES to a particular consumer, first determine the values of the begin and end power in the ith branch of the power system from (1):

$$\dot{S}_{bi} = \sqrt{3}(\dot{U}_d\mathbf{M}_{\Sigma i})\hat{I}_i\,, \qquad (2)$$

where $\mathbf{M}_{\Sigma i}$ is a vector-column of the matrix of branch connections in nodes $\mathbf{M}_{\Sigma}$; $\hat{I}_i$ is the current in the i-th branch.

The peculiarity of the method is the use of a matrix of coefficients of power distribution of nodes over the branches of the power grid $\dot{D}$. The vector-row $\dot{D}$ is determined by the formula [26]:

$$\dot{D}_i = (\dot{U}_d\mathbf{M}_{\Sigma i})\hat{C}_i\dot{U}_d^{-1}\,, \qquad (3)$$

where vector-row $\dot{D}_i$ consists of coefficients that represent the share of the total power of the i-th branch that is caused by the power flowing through it from each node.

Taking into account (3), the capacities in the i-th branch will be determined as:

$$\dot{S}_{bi} = \dot{D}_i\dot{S}\,. \qquad (4)$$

In general, we can write that

$$\dot{S}_b = \dot{D}\dot{S}\,, \qquad (5)$$

where $\dot{D}$ is a matrix of coefficients of power distribution of nodes over the branches of the power grid, which is formed from n rows $\dot{D}_i$, n is number of branches in the power grid. In accordance with the mathematical model for determining the origin of electricity, the algorithm described in [27, 28] was developed.

3. Results and Discussion

In order to study the possibility of applying the method of determining the origin of consumer electricity from renewable energy sources and demonstrating its effectiveness for circuit grids of different voltages [29-32], consider a 14-node IEEE grid with 15 MW photovoltaic power plants installed at 6 and 8 nodes, shown in Fig. 1. The balancing node is node 1. The control calculation of the steady-state mode for the maximum generation of the PV plant was performed by the PowerFactory 15.1 program. Based on the results of the steady-state calculation, the voltages of the nodes are determined. We assume that the first node is powered by low-carbon energy sources, in our case by a nuclear power plant, and the 2nd node is powered by a source with a high carbon footprint. We calculate the power flows through the branches of the circuit, taking into account their origin, for the considered grid scheme.

In order to reduce the size of the matrices obtained as a result of the calculation, we present only the active component of the required capacities. Using the values of the calculated node voltages, we calculate the power distribution coefficient matrix (3):

$D =$

	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.822	0.76	0.657	0.593	0.453	0.492	0.477	0.486	0.483	0.47	0.458	0.462	0.478
2	–0.03	0.583	0,147	0.099	0.086	0.119	0.115	0.116	0.112	0.1	0.089	0.092	0.107
3	–0.06	0.108	0.3	0.202	0.17	0.234	0.226	0.228	0.219	0.196	0.175	0.18	0.209
4	–0.081	0.044	0.188	0.272	0.203	0.148	0.143	0.152	0.161	0.182	0.201	0.197	0.173
5	0.172	0.268	0.368	0.424	0.325	0.287	0.278	0.289	0.296	0.311	0.324	0.322	0.306
6	0.081	0.28	0.497	–0.272	–0.137	0.373	0.361	0.328	0.252	0.066	–0.107	–0.067	0.159
7	0.03	0.417	–0.147	–0.099	–0.086	–0.119	–0.115	–0.116	–0.112	–0.1	–0.089	–0.092	–0.107
8	–0.008	–0.029	–0.05	0.027	–0.872	–0.074	–0.071	–0.136	–0.261	–0.557	–0.836	–0.777	–0.42
9	0.004	0.011	0.017	–0.002	–0.017	–0.763	–0.732	–0.174	–0.149	–0.086	–0.028	–0.042	–0.491
10	0.003	0.017	0.032	0.028	–0.109	–0.159	–0.152	–0.696	–0.602	–0.366	–0.149	–0.2	0.118
11	–0.004	–0.011	–0.016	–0.002	0.017	–0.232	–0.221	0.171	0.146	0.084	0.028	0.041	0
12	0	0	0	0	0	0	–0.957	0	0	0	0	0	–0.023
13	0.004	–0.017	–0.03	0.016	0.077	–0.044	–0.042	–0.081	0.779	0.442	0.068	0.055	–0.023
14	–0.005	–0.018	–0.03	0.016	0.077	–0.045	–0.043	–0.082	–0.222	0.444	0.069	0.055	0.023
15	0.005	0.018	0.03	–0.016	–0.077	0.045	0.043	0.082	0.222	0.556	–0.069	–0.055	0.618
16	–0.003	–0.011	–0.018	0.01	0.047	–0.027	–0.026	–0.05	–0.034	0.005	0.106	0.181	0.073
17	0	0.002	0.003	–0.002	–0.009	0.005	0.005	0.01	0.006	–0.001	0.624	0.153	–0.007
18	0	0	0	0	0.001	0	0	–0.001	0	0	–0.005	–0.014	–0.006
19	0	0	0	0	0.001	0	0	–0.001	0	0	0.002	0.003	0
20	0	0	0	0	0	0	0	0	0	0	0.002	0	

Multiplying the matrix of power distribution coefficients of nodes by the vector-column of load and generation in nodes, we obtain the matrix of power distribution across the branches of the power grid, including from LCES:

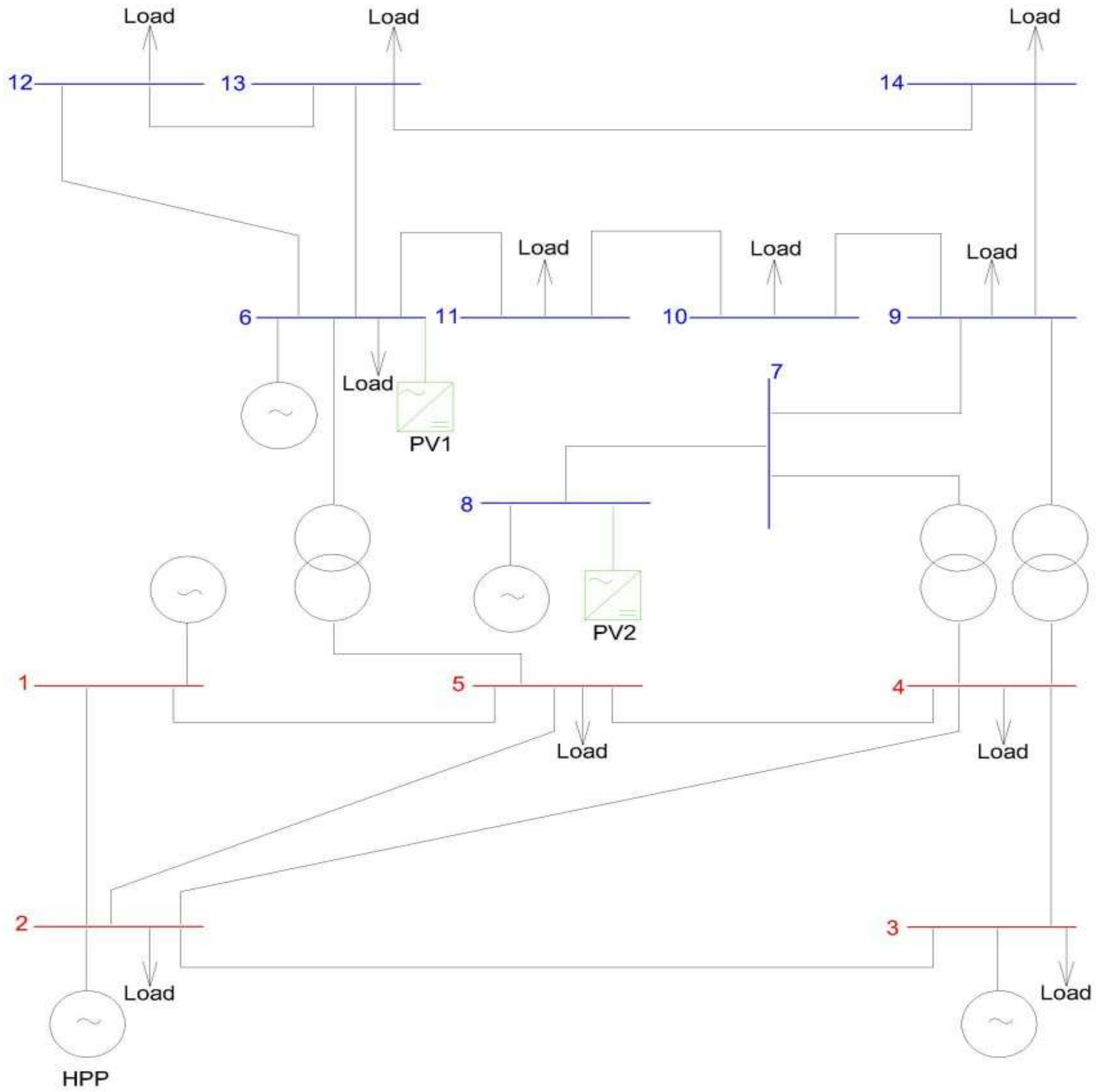

Fig.1. Electrical grid scheme

$S =$

	2	3	4	5	6	7	8	9	10	11	12	13	14
1	–15.05	72.35	31.55	4.51	–2.08	–11.21	0	17.54	5.32	2.0	3.4	7.62	8.85
2	0.54	54.95	7.07	0.76	–0.37	–2.49	0	3.84	1.13	0.39	0.61	1.39	1.8
3	1.11	10.23	14.33	1,53	–0.75	–5.05	0	7.78	2.29	0.79	1.23	2.81	3.65
4	1.49	4.12	8.97	2.06	–0.89	–3.25	0	5.27	1.71	0.75	1.45	3.15	3.07
5	–3.15	25.38	17.58	3.22	–1.43	–6.31	0	10.03	3.14	1.28	2.33	5.13	5.43
6	–1.48	26.5	23.83	–2.06	0.51	–8.02	0	11.25	2.63	0.27	–0.8	–1.1	2.8
7	–0.54	39.25	–7.07	–0.76	0.37	2.49	0	–3.84	–1.13	–0.39	–0.61	–1.39	–1.8
8	0.2	–3.1	–2.8	0.27	3.12	1.63	0	–4.37	–2.42	–1.93	–5.05	–10.32	–6.25
9	–0.02	0.31	0.33	–0.09	0.18	14.09	0	–6.24	–1.68	–0.39	–0.27	–0.83	–2.14
10	–0.17	2.76	2.44	–0.18	0.49	3.37	0	–19.04	–5.01	–1.21	–0.88	–2.61	–6.98
11	0.02	–0.3	–0.32	0.08	–0.18	4.98	0	6.14	1.65	0.39	0.26	0.81	2.11
12	0	0	0	0	0	19.15	0	0	0	0	0	0	0
13	0.12	–1.87	–1.69	0.16	–0.41	0.98	0	–2.64	6.96	1.59	0.45	0.85	–0.34
14	0.12	–1.88	–1.7	0.16	–0.41	0.99	0	–2.65	–2.05	1.57	0.45	0.85	–0.34
15	–0.12	1.88	1.7	–0.16	0.41	–0.99	0	2.65	2.05	1.93	–0.45	–0.85	0.34
16	0.07	–1.15	–1.04	0.1	–0.25	0.61	0	–1.62	–0.34	0.03	0.67	2.51	9.21
17	–0.01	0.22	0.2	–0.02	0.05	–0.12	0	0.31	0.06	–0.01	3.8	2.05	1.08
18	–0.06	0.95	0.86	–0.08	0.21	–0.5	0	1.34	0.28	–0.02	1.61	8.91	4.7
19	–0.07	1.15	1.04	–0.1	0.25	–0.61	0	1.62	0.34	–0.03	–0.67	–2.51	5.69
20	–0.01	0.22	0.2	–0.02	0.05	–0.11	0	0.31	0.06	–0.01	–2.29	2.04	1.08

The values of the elements in the columns of the matrix show the distribution of power by branches of the scheme from LCES, which makes it possible to determine by calculation what share of “clean” electricity was consumed by a particular consumer. Thus, using the example of load consumption at node 9, it can be determined that 5.64 MW was received from PV (of which 0.66 MW from PV 1, 4.98 MW from PV 2), 0.19 MW flowed from the second node from the thermal power plant (TPP) to node 9, and the rest was received from the NPP. For comparison, consider the load coverage at node 5.

According to the calculations, the flow from TPP to node 5 is 2.97 MW, the rest is covered by the balancing node. Based on the fact that node 9 consumes 29.5 MW, and node 5 - 7.6 MW, the percentage of power received from LCES to the total load power is as follows: for node 5 - 40%, for node 9 - 99%, 20% of which is from PV. Further, having the matrix of power distribution across the branches of the power grid, it is also possible to determine the matrix of power losses caused, among other things, by the flow from LCES. The total active power losses calculated by the matrix method amount to 12.3 MW, while the results of the steady-state calculation using the Power Factory complex are 12.37 MW, which confirms the adequacy of the proposed method.

Conclusions

Determining the amount of electricity received by a consumer from LCES is necessary to confirm its origin, which will allow manufacturers to produce products with green labelling. Energy large consumption manufactures (for example, metallurgy sector) will be paid additional tax from 2025, because they produce a lot of CO_2. This tax will be added when they will sale production in EU market. Proposed method will help motivate enterprises consume energy, which produce by LCES.

The article presents a method for calculating individual components of electricity flows in the branches of an electric grid circuit caused by generation and consumption in the nodes. The method determines the share of electricity consumption of a particular electricity consumer that is provided by energy sources with a low carbon footprint connected to the power grid. The method is based on a mathematical model for determining the power distribution coefficients of low-carbon energy sources in the branches of the power grid. The described method can serve as a tool to confirm the guarantees of the origin of the consumed energy.

Since LCES use general power grids to transmit the generated electricity, determining their share of power in power flows to consumers allows taking into account the impact of LCES on the parameters of the power system mode and can be used in the operational planning of the electricity balance. The results of calculations of the 14-node IEEE circuit by the matrix method were confirmed by the results of computer modelling in the Power Factory software complex.

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