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CONSTRUCTION OF A PARAMETERIZED ANALYTICAL MODEL FOR FULL LIFE-CYCLE EMISSIONS ASSESSMENT IN CLIMATE COMPARISON OF ENERGY SOLUTIONS FOR TRANSPORT SYSTEMS

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This study investigates the process of assessing the climate efficiency of alternative energy solutions in transport systems within the full life-cycle Well-to-Wheel (WTW) approach.

The task addressed relates to the methodological inconsistency of climate comparison results when applying the Tank-to-Wheel (TTW) approach, which considers only operational emissions and neglects upstream components associated with the production and supply of energy resources. This leads to a systemic gap between estimated and actual full life-cycle climate effects of energy alternatives.

A parameterized analytical model of climate comparability, the WTW Climate Comparability Model (WTW-CCM), has been built to formalize the dependence of full life-cycle emissions on energy chain parameters. The structure of full life-cycle emissions is substantiated as the sum of Well-to-Tank, Tank-to-Wheel, and specific components. The model is aligned with international methodological frameworks EN 16258, the GLEC Framework, and ISO 14083.

The climate efficiency of energy solutions has been shown to be parameter-dependent and determined by the carbon intensity of the energy system and methane slip emissions. A threshold criterion in the form of a critical grid carbon intensity has been derived. It is demonstrated that electric solutions become climate-efficient only under specific parametric conditions.

The possibility of inversion of climate efficiency of alternatives has been demonstrated. The phenomenon of decarbonization investment asymmetry has been formalized; the DIAI index has been proposed for the quantitative assessment of distortions in investment signals. It was substantiated that different assessment boundaries (TTW and WTW) lead to the formation of incommensurable investment priorities.

The practical significance includes the application of the model for substantiating managerial and investment decisions in transport decarbonization

Keywords: Well-to-Wheel (WTW), transport decarbonization, life-cycle emissions, decarbonization investment asymmetry, transport technologies

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1. Introduction

Assessment of the climate impact of energy solutions is one of the key tools for shaping the decarbonization policy of the transport sector. Under today's conditions of increasing requirements for reducing greenhouse gas emissions, ensuring the correctness of such an assessment is of particular scientific and practical importance. The practical significance of the above-mentioned approach is manifested in a wide range of economic activities, in particular in maritime, inland waterway, and road transport, port activities, as well as in energy supply systems of transport infrastructure. The assessments obtained on its basis are used to substantiate strategic and operational decisions, in particular the choice of the type of energy supply for vehicles, determining the feasibility of electrification, the introduction of alternative fuels (in particular LNG), as well as the formation of investment programs for the development of transport and port systems. In addition, the results of such an assessment are used in the development of state decarbonization policy, the establishment of regulatory requirements, and the formation of mechanisms for stimulating low-carbon technologies.

Traditionally, the assessment is based on the Tank-to-Wheel (TTW) approach, which takes into account only emissions arising from the direct use of energy by a vehicle. However, this approach does not cover emissions associated with the production, processing, and transportation of energy resources, which can form a significant share of the total climate impact.

Unlike TTW, the Well-to-Wheel (WTW) approach takes into account the entire energy chain – from the extraction and production of energy resources to their final use – and provides a more systematically consistent assessment of the climate efficiency of alternative energy solutions.

The methodological difference between the TTW and WTW approaches is determined by the boundaries of the assessment system, which directly affects the results of comparing alternatives. The use of the TTW approach can lead to the formation of distorted ideas about the climate efficiency of energy solutions and, accordingly, to the adoption of inefficient management and investment decisions in the field of decarbonization of transport.

In this regard, ensuring the climate comparability of alternative energy solutions in transport systems requires the use of more comprehensive assessment approaches that take into account the entire energy chain and the specifics of transport and technological processes.

Thus, research aimed at improving methodological approaches to assessing the climate efficiency of energy solutions in transport systems is relevant both from a scientific and practical point of view.

2. Literature review and problem statement

Strengthening climate policy and decarbonization commitments in the transport sector is actively considered in international analytical studies and strategic energy scenarios (in particular, IEA [1, 2]), which envisage a deep transformation of energy and transport systems towards achieving climate neutrality. This leads to increased investment in alternative energy solutions – in particular, the use of liquefied natural gas (LNG), electrification of transport systems and other low-carbon technologies. At the same time, the justification for such investments is often based on direct operational emissions (Tank-to-Wheel, TTW), which creates the risk of incomplete assessment of their real climate effect. However, in those studies, the main focus is on scenario modeling of energy system transformation, while the issues of parameterized assessment of the climate effectiveness of alternative energy solutions in transport remain insufficiently formalized. The most likely reason is the complexity of integrating multi-component energy chains into a single analytical model.

Modern energy alternatives differ significantly in the structure of the energy chain, the presence of non-CO_2 components (in particular methane in the case of LNG), and the dependence on the parameters of the energy system (in the case of electrification of transport). Assessment within the TTW may cause methodological asymmetry because ignoring upstream components leads to a distortion of the assessment of the climate impact of alternatives.

Despite the development of international standards for the assessment of transport emissions (EN 16258, GLEC Framework, ISO 14083), the issue of systemic comparability of alternatives, taking into account the threshold conditions of their climate feasibility and parametric stability of the results, remains insufficiently formalized. In particular, there is no unified analytical approach that integrates upstream emissions, methane slip emissions, and energy system parameters into a single WTW model for assessing alternatives in transport systems.

The methodological basis for accounting for energy consumption and emissions in transport services in Europe is laid down by the EN 16258 standard [3]. It provides for the possibility of calculating indicators both on an operational basis (TTW) and taking into account the full energy chain (Well-to-Tank / Well-to-Wheel). At the same time, this standard regulates the calculation procedures but does not provide analytical formalization of the comparison of alternatives, which limits the possibility of assessing the parametric sensitivity of the results.

Further developments (GLEC [4], ISO 14083 [5]) expand the methodological framework but remain descriptive in nature and do not form a generalized parameterized toolkit for comparing alternatives. An important stage in the development of the WTW approach was the study by the JEC Consortium [6], which performed a comprehensive life cycle analysis of alternative fuels and power plants in the European context.

Life cycle studies on alternative fuels confirm a significant difference between the results of the assessment within the TTW and WTW. In particular, work [7] shows that the full-cycle emissions of alternative fuels are largely determined by the upstream component and parameters of the power system. Study [8] demonstrates that the assessment of alternative transport technologies based on TTW can lead to significant differences compared to the results of the full-cycle WTW analysis. However, those studies are mainly applied in nature and are not aimed at building a universal analytical model.

A separate problematic block of WTW assessment is the methane factor in gas technologies. Work [9] emphasizes the importance of methane and CO_2 emissions in the natural gas supply chain, and paper [10] substantiates that the choice of climate metrics and time horizons significantly affects the final climate result. In [11] it is shown that the use of LNG as a marine fuel can provide lower operational emissions within the TTW, however, the full-cycle climate effect depends on the parameters of methane slip emissions and the conditions of fuel production and transportation.

Despite this, there is no generalized analytical model that makes it possible to integrate methane slip emissions into the system of comparing alternatives, which is due to the high variability of the parameters and the uncertainty of their assessment.

The conversion of methane into CO_2-equivalent is determined according to the IPCC estimates [12], which provide the values of the global warming potential (GWP) for different time horizons, which directly affects the results of the WTW assessment.

In [13], the issue of decarbonization of the maritime industry is considered in the context of the interaction of global environmental initiatives and local practices of their implementation. It is shown that achieving decarbonization goals in the maritime sector requires systematic consideration of technological, energy and regulatory factors. However, in [13], the dependence of the climate effect on the parameters of the energy chain is not formalized and the analytical tools for WTW assessment are not proposed. The most likely reason is the focus of the study on macro-level decarbonization trends, rather than on the construction of formalized models.

In [14], Smart Ports are studied as an innovative vector of technological transformation and digitalization of ports. It is substantiated that the intellectualization of port activities is associated with increasing the efficiency of transport and technological processes and creates the prerequisites for the environmental modernization of the port sector. At the same time, work [14] does not establish an analytical connection between the climate effect and the parameters of the energy chain, and does not determine the threshold conditions for the climate feasibility of alternatives. This is explained by the fact that the subject of the study is the digital and technological transformation of ports, and not the analytical modeling of full-cycle emissions.

Work [15] specifies the concept of “Smart Port” in the context of global trends in the integration of intelligent transport and information technologies in the port industry. It is shown that the modern port industry is developing in the direction of a complex combination of transport, information, and management solutions. However, the work does not contain a formalized parameterized model that would allow compare energy alternatives according to the criterion of full-cycle climate feasibility. The most likely reason is the conceptual nature of the study, aimed at specifying the categorical apparatus.

As a result of our analysis, it was found that the existing approaches to WTW assessment are mainly descriptive or procedural in nature and do not provide a formalized parameterized toolkit for a consistent analytical comparison of energy alternatives in transport systems.

In particular, the approaches that allow for the following are still insufficiently developed:

– to systematically compare energy alternatives taking into account the full energy chain;

– to integrate upstream emissions, methane slip emissions, and energy system parameters into a single model;

– to determine the threshold conditions of climate feasibility of alternatives;

– to analyze the parametric sensitivity of the results;

– to assess the impact of the assessment boundaries (TTW or WTW) on investment decisions.

In this regard, the concept of investment asymmetry of decarbonization (IAD) is introduced, which arises due to different assessment boundaries (TTW and WTW) and leads to distortion of investment signals.

Thus, an unsolved scientific problem has been identified, which is essentially the lack of a generalized parameterized analytical model of the climate comparability of energy alternatives in transport systems, which necessitates designing an appropriate toolkit.

3. The aim and objectives of the study

The aim of our research is to construct a parameterized analytical model of climate comparability of energy solutions in transport systems, which reflects the dependence of the results of the full-cycle assessment on the parameters of the energy chain and determines the threshold conditions of their climate feasibility. This will make it possible to formalize the analytical comparison of alternative energy solutions, increase the validity of the assessment of their climate effect, and provide support for making investment decisions in the field of decarbonization of transport systems.

In accordance with the set goal, the following tasks have been formulated:

– to formalize the parameterized WTW assessment model – WTW Climate Comparability Model (WTW-CCM), consistent with the international methodological frameworks EN 16258, GLEC Framework and ISO 14083, and to determine a system of variables for comparing energy alternatives in transport systems;

– to determine the threshold conditions of climate feasibility of alternatives within the WTW approach and formalize the criterion of critical carbon intensity of the electricity grid EF_{grid}^{crit};

– to assess the parametric sensitivity and stability of the WTW comparison results on demonstration scenarios for LNG and traditional fuels (road / IWT / sea) taking into account methane slip emissions and upstream components of the energy chain;

– to formalize the phenomenon of investment asymmetry of decarbonization as a consequence of the use of Tank-to-Wheel indicators when justifying investments in transport systems and assess its manifestation within the parameterized WTW model.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of assessing the climate efficiency of alternative energy solutions in transport systems within the complete energy chain (Well-to-Wheel, WTW).

The main hypothesis of the study assumes that the climate comparability of alternative energy solutions is determined by the parameters of the energy chain and can be represented in the form of a parameterized analytical model.

The following assumptions are adopted in the study:

– energy parameters are considered as generalized (reference), corresponding to typical conditions of operation of transport systems;

– the assessment is carried out within the energy life cycle (WTW) without taking into account the production and disposal of vehicles;

– greenhouse gas emissions are given in CO_2 equivalent using standard global warming potential (GWP) coefficients.

The accepted simplifications include:

– aggregation of individual components of the energy chain into parameterized components;

– generalized representation of methane slip emissions for LNG solutions.

4. 2. Methodological basis of the study

The methodological basis of our study is international standards for assessing energy consumption and greenhouse gas emissions in transport systems, in particular EN 16258 (CEN, EU), GLEC Framework (Smart Freight Centre, The Netherlands), and ISO 14083 (ISO, Switzerland).

To take into account non-CO_2 components, in particular CH_4 in gas technologies, the selection of climate metrics and assessment time horizons, the IPCC (Intergovernmental Panel on Climate Change, UN, Switzerland) approaches and the results of methane slip emissions studies were used.

The study considers three generalized types of energy solutions in transport systems:

– conventional fuel solutions;

– LNG solutions;

– electrical solutions for which the climate effect is determined by the parameters of the electricity system and its carbon intensity.

The comparison of alternatives is carried out within the parameterized Well-to-Wheel (WTW) approach.

The following system boundaries were used in our study:

– Tank-to-Wheel (TTW) – operational emissions when using energy in a vehicle;

– Well-to-Tank (WTT) – upstream emissions associated with the extraction or production, processing, transportation, and preparation of an energy resource;

– Well-to-Wheel (WTW) – total climate impact within the energy chain, defined as the sum of Well-to-Tank, Tank-to-Wheel, and specific non-CO_2 emissions components (for gas technologies).

The functional unit is specific emissions per transport work: $gCO_2e/(t{\cdot}km)$, where transport work is defined as the product of the mass of the cargo and the distance of transportation: $(Q \cdot L)$, where Q is the mass of the cargo (t), L is the distance of transportation (km).

For maritime transport, where distance is traditionally given in nautical miles, unification to the SI system was performed: $1\ \text{nm}i = 1.852$ km, respectively, the distance was converted to kilometers to ensure comparability of results.

For a formal comparison of alternative energy solutions, the study used a parameterized analytical apparatus designated as the WTW Climate Comparability Model (WTW-CCM).

To ensure analytical consistency of the study, a notation system has been introduced, which is used to formalize the assessment of full-cycle emissions of alternative energy solutions and build an analytical model of their climate comparability.

Let j be an alternative energy solution for a certain transport system. The following main notations are used in the study:

E^j_{TTW} – specific greenhouse gas emissions within the Tank-to-Wheel approach for energy solution j, $gCO_2e/(t{\cdot}km)$;

E^j_{WTT} – specific greenhouse gas emissions within the Well-to-Tank approach for energy solution j, $gCO_2e/(t{\cdot}km)$;

E^j_{WTW} – specific full-cycle emissions within the Well-to-Wheel approach for energy solution j, $gCO_2e/(t{\cdot}km)$;

E^j_{spec} – specific component of full-cycle emissions characteristic of the corresponding energy solution j, $gCO_2e/(t{\cdot}km)$;

E^{LNG}_{slip} – methane component of full-cycle emissions of the LNG solution (methane slip emissions), converted to CO_2 equivalent, $gCO_2e/(t{\cdot}km)$;

EF_{grid} – carbon intensity of the electricity grid, gCO_2e/kWh;

EC – specific electricity consumption for transport work, kWh/(t km);

GWP_{CH_4} – global warming potential of methane for the adopted time horizon;

F – fuel consumption per transport operation or voyage;

FC – energy consumption of the fuel transport system or vehicle;

EF_{comb} – emission factor for fuel combustion;

$EF^{CH_4}_{slip}$ – specific methane slip emissions factor, gCH_4 per unit of energy;

Q – mass of transported cargo, t;

L – transportation distance, km.

To describe the climate comparability of two alternative energy solutions, the notations A and B are used, and

$$A,B \in \{diesel, HFO, MGO, LNG, electric,...\}.$$

This notation is used for a unified description of different types of transport systems and technological configurations.

The model is applied to different types of comparisons of alternatives, in particular: traditional fuel – LNG; LNG – electric; MGO – LNG; diesel – electric, etc.

4. 3. Methodology for the study of comparative scenarios

The study applied a scenario approach to the comparison of alternative energy solutions, which involved the analysis of various combinations of energy chain parameters within generalized transport systems.

The comparison of alternatives was carried out for typical scenarios, which include a combination of the following energy solutions:

- traditional fuel solutions;
- LNG solutions;
- electric solutions.

For each scenario, the unity of the functional unit of assessment and the consistency of the system boundaries (TTW, WTT, WTW) were ensured, which allowed for a correct comparison of alternatives.

Within the scenario approach, generalized (reference) parameter values were used that correspond to typical conditions of operation of transport systems and accepted international standards for emission assessment.

The scenarios were formed in such a way as to ensure the comparability of alternatives under the same conditions of operation of the transport system.

4. 4. Parametric analysis methodology

In the parametric analysis procedure, the variation of parameters was carried out in realistic intervals of values characteristic of the relevant energy systems, technological configurations, and scenario assumptions.

For each combination of parameters, the value of the climate comparability function $\Delta_{A,B}$ was determined and the change or preservation of its sign was checked.

For LNG solutions, the key parameters included the characteristics of the upstream component and methane slip emissions.

For electrical solutions, the determining parameters were:

- carbon intensity of the electricity grid EF_{grid};
- specific electricity consumption EC.

For traditional fuel solutions, the parametric analysis covered the variation of the components E_{WTT}, E_{TTW} and other characteristics of the fuel chain depending on the adopted research formulation.

4. 5. Approach to assessing investment effects

To assess the impact of the choice of the boundaries of the climate impact assessment system on the results of comparing alternatives, an approach based on the use of a system of analytical indicators was applied.

This approach allowed us to take into account:

- the methodological gap between the TTW and WTW approaches;
- differences in assessing the decarbonization benefit of alternative solutions;
- potential investment consequences arising from the use of different assessment boundaries.

The assessment of investment effects was carried out by comparing the results obtained within the framework of different approaches to determining climate impact, in order to identify possible distortions in the formation of investment decisions.

The assessment was carried out in relative indicators, which provided the possibility of comparing alternative solutions with each other.

5. Results of investigating the climate comparability of energy solutions in transport systems

5. 1. Formalization of the model of climate comparability of energy solutions

Formalization of specific operational emissions within the TTW approach.

Within the Tank-to-Wheel (TTW) approach, it is established that direct operational emissions are formed directly during the use of an energy solution in the transport process. In general, specific TTW emissions are represented in the form of the ratio of total direct operational emissions to the volume of transport work performed

$$E^{j}_{TTW} = \frac{E^{j}_{direct}}{Q \cdot L}, \tag{1}$$

where E^{j}_{TTW} – specific operational emissions of energy solution j, gCO$_2$e/(t·km);

E^{j}_{direct} – total direct operational emissions arising from the use of energy solution j during a voyage or transport operation, gCO$_2$e;

Q – mass of transported cargo, t;

L – transportation distance, km.

For fuel solutions, the value of direct operational emissions is specified through fuel consumption and emission factor during its combustion

$$E^{fuel}_{direct} = F \cdot EF_{comb}, \tag{2}$$

where F is the fuel consumption per transport operation or voyage in agreed units;

EF_{comb} is the emission factor for fuel combustion.

For electric solutions, the general form of expression (1) is preserved, however, in this case there are no direct operational emissions, that is, $E^{el}_{direct} = 0$.

Formalization of full-cycle emissions within the WTW approach.

It is established that the Well-to-Wheel (WTW) approach, unlike the Tank-to-Wheel (TTW), covers the full energy cycle of energy use and includes both operational and upstream emissions associated with the extraction, processing, and transportation of energy resources. In general, the specific full-cycle emissions for energy solution j are given as the additive sum of the components of individual phases of the energy cycle

$$E^{j}_{WTW} = E^{j}_{WTT} + E^{j}_{TTW} + E^{j}_{spec}, \tag{3}$$

where E^{j}_{WTW} – specific full-cycle greenhouse gas emissions for energy solution j, gCO$_2$e/(t·km);

E^{j}_{WTT} – specific emissions of the Well-to-Tank phase, arising at the stages of production and supply of the energy carrier;

E^{j}_{TTW} – specific emissions of the Tank-to-Wheel phase, formed directly during the use of the energy carrier in the transport process;

E^{j}_{spec} – a specific component of full-cycle emissions, characteristic of the corresponding type of energy solution.

The index j is used to denote the type of energy solution belonging to the set $j \in \{diesel, HFO, MGO, LNG, electric\}$.

For traditional liquid fuels in a simplified formulation, it is accepted

$$E^{j}_{spec} = 0, \quad j \in \{diesel, HFO, MGO, \ldots\}. \tag{4}$$

In this case, the full-cycle emissions were determined by the sum of the WTT and TTW components.

For gas energy solutions, it was found that the specific component of the full-cycle emissions for LNG solutions is a non-zero and climate-significant value, which significantly affects the result of the full-cycle assessment. In this case

$$E^{LNG}_{spec} = E^{LNG}_{slip} \neq 0. \tag{5}$$

Accordingly, the full-cycle emissions of the LNG solution are given as

$$E^{LNG}_{WTW} = E^{LNG}_{WTT} + E^{LNG}_{TTW} + E^{LNG}_{slip}. \tag{6}$$

The methane component of full-cycle emissions E^{LNG}_{slip} is given as the mass of unburned methane, converted to CO$_2$ equivalent according to the adopted $GWP_{\mathrm{CH_4}}$ value

$$E^{LNG}_{slip} = m_{\mathrm{CH_4}} \cdot GWP_{\mathrm{CH_4}}, \tag{7}$$

where $m_{\mathrm{CH_4}}$ – mass of unburned methane in exhaust gases, CH$_4$;

$GWP_{\mathrm{CH_4}}$ – global warming potential of methane.

The mass of unburned methane is expressed in terms of vehicle energy consumption and the specific coefficient methane slip emissions

$$m_{\mathrm{CH_4}} = FC \cdot EF^{\mathrm{CH_4}}_{slip}, \tag{8}$$

where FC is the energy consumption of the vehicle or transport system;

$EF^{\mathrm{CH_4}}_{slip}$ is the specific coefficient of methane slip emissions.

Substituting expressions (7) and (8) yields a parameterized expression for the methane component of full-cycle emissions of LNG solutions

$$E^{LNG}_{slip} = FC \cdot EF^{\mathrm{CH_4}}_{slip} \cdot GWP_{\mathrm{CH_4}}. \tag{9}$$

In functional form, the dependence of the methane component was written as follows

$$E^{LNG}_{slip} = f\left(FC, EF^{\mathrm{CH_4}}_{slip}, GWP_{\mathrm{CH_4}}\right). \tag{10}$$

The coefficient $GWP_{\mathrm{CH_4}}$ is adopted in accordance with the current IPCC estimates.

Parameterization of electric energy solutions.

It was found that for electric energy solutions within the TTW approach there are no direct greenhouse gas emissions. Accordingly, the specific emissions within the Tank-to-Wheel approach were equal to zero

$$E^{el}_{TTW} = 0. \tag{11}$$

Taking into account the general structure of WTW-evaluation (3) for electrical solutions, an analytical expression was obtained

$$E^{el}_{WTW} = E^{el}_{WTT} + E^{el}_{TTW} + E^{el}_{spec}. \tag{12}$$

Since $E^{el}_{TTW} = 0$, and specific component for electrical solutions is absent in the simplified formulation $\left(E^{el}_{spec} = 0\right)$, full-cycle emissions were determined exclusively by the upstream component

$$E^{el}_{WTW} = E^{el}_{WTT}. \tag{13}$$

In parameterized form, the full-cycle emissions of electrical solutions are written as

$$E^{el}_{WTT} = EC \cdot EF_{grid}, \tag{14}$$

where EC is the specific electricity consumption for transport work, kWh/(t km);

EF_{grid} is the carbon intensity of the electricity system, gCO$_2$e/kWh.

The dimensionality of expression (14) is defined as

$$\mathrm{kWh}/\left(\mathrm{t{\cdot}km}\right)\times \mathrm{gCO^2e/kWh} = \mathrm{gCO^2e}/\left(\mathrm{t{\cdot}km}\right). \tag{15}$$

Formalization of the WTW-CCM climate comparability model.

The expansion of the system boundaries from the Tank-to-Wheel (TTW) to Well-to-Wheel (WTW) approach was formally interpreted as the inclusion of additional stages of the energy cycle, which was conceptually represented as a nested set ratio

$$TTW \subset WTW. \tag{16}$$

The WTW assessment framework was used as a methodological basis for building a parameterized analytical model of the climate comparability of alternative energy solutions – the WTW Climate Comparability Model (WTW-CCM).

Within this model, the climate advantage of alternative energy solutions is defined as the difference in full-cycle emissions of alternative energy solutions

$$\Delta_{A,B} = E_{WTW}^{A} - E_{WTW}^{B}, \tag{17}$$

where A and B are alternative energy solutions being compared.

Thus, the function $\Delta_{A,B}$ acts as a generalized criterion for the climatic comparability of alternatives within the WTW approach:

– if $\Delta_{A,B} < 0$, then solution A is climatically better;

– if $\Delta_{A,B} > 0$, then solution B is climatically better;

– if $\Delta_{A,B} = 0$, then solutions A and B are climatically equivalent.

In a parameterized form, the generalized analytical model is represented as a function of sets of parameters that determine the structure of the energy chain and the conditions for the operation of the transport system

$$\Delta_{A,B} = f\left(\Theta_A, \Theta_B\right), \tag{18}$$

where Θ_A and Θ_B are sets of parameters characterizing alternatives A and B.

Based on the structure of WTW emissions (3) and the parameterization of electrical solutions (14), a system of analytical dependences has been formed, which allows for a consistent comparison of alternative energy solutions.

For the case of comparing electrical and fuel solutions, the model is represented in the following form

$$\Delta_{el,fuel} = E_{WTW}^{el} - E_{WTW}^{fuel}. \tag{19}$$

Taking into account expressions (3) and (14), we obtain

$$\Delta_{el,fuel} = EC \cdot EF_{grid} - \left(E_{WTT}^{fuel} + E_{TTW}^{fuel} + E_{spec}^{fuel}\right). \tag{20}$$

For traditional liquid fuels, in a simplified formulation, it is accepted

$$E_{spec}^{fuel} = 0, \tag{21}$$

for LNG solutions, respectively, we obtain

$$E_{spec}^{fuel} = E_{slip}^{LNG}. \tag{22}$$

The methane component is represented in a parameterized form

$$E_{slip}^{LNG} = FC \cdot EF_{slip}^{\mathrm{CH_4}} \cdot GWP_{\mathrm{CH_4}}. \tag{23}$$

For the case of comparing a traditional fuel solution and an LNG solution, the model is represented in the form

$$\Delta_{conv,LNG} = E_{WTW}^{conv} - E_{WTW}^{LNG}. \tag{24}$$

After substituting the corresponding components of full-cycle emissions, we obtain

$$\Delta_{conv,LNG} = \left(E_{WTT}^{conv} + E_{TTW}^{conv}\right) - \left(E_{WTT}^{LNG} + E_{TTW}^{LNG} + E_{slip}^{LNG}\right). \tag{25}$$

For the case of comparing the LNG solution and the electric solution, we obtained

$$\Delta_{LNG,el} = E_{WTW}^{LNG} - E_{WTW}^{el}. \tag{26}$$

Accordingly, it is written

$$\Delta_{LNG,el} = \left(E_{WTT}^{LNG} + E_{TTW}^{LNG} + E_{slip}^{LNG}\right) - EC \cdot EF_{grid}. \tag{27}$$

The generalized climate comparability function is given as

$$\Delta_{A,B} = E_{WTW}^{A} - E_{WTW}^{B}. \tag{28}$$

The resulting system of relations (1) to (28) forms a formalized analytical basis for the WTW Climate Comparability Model (WTW-CCM) and provides the possibility of further deriving threshold conditions for the climate feasibility of alternative energy solutions.

5. 2. Threshold conditions for the climate feasibility of electric solutions

The climate advantage of the electric solution within the WTW approach is determined on the basis of an analytical relation that reflects the difference in full-cycle emissions of alternative energy solutions

$$E_{WTW}^{el} < E_{WTW}^{fuel}. \tag{29}$$

The threshold value of the carbon intensity of the electricity grid is determined from the condition of climatic equivalence of alternatives, which corresponds to the zero value of the climatic comparability function $\Delta_{A,B} = 0$

$$E_{WTW}^{el} = E_{WTW}^{fuel}. \tag{30}$$

After substituting analytical expressions for the electrical and fuel solutions into (30), an analytical expression was obtained for determining the critical carbon intensity of the power grid EF_{grid}^{crit}

$$EF_{grid}^{crit} = \frac{E_{WTW}^{fuel}}{EC} = \frac{E_{WTT}^{fuel} + E_{TTW}^{fuel} + E_{spec}^{fuel}}{EC}. \tag{31}$$

In the case of comparison with the LNG solution, the methane component E_{slip} is included in the corresponding full-cycle emissions indicator E_{WTT}^{fuel}, which ensures that non-$\mathrm{CO_2}$ components of the climate impact are taken into account.

Accordingly, the condition for the climate advantage of the electric solution is written as an inequality

$$EF_{grid} < EF_{grid}^{crit}. \tag{32}$$

Within the proposed model, three modes of climatic comparability of electric and fuel solutions are analytically identified, which are determined by the relative position of the actual EF_{grid} value relative to the critical threshold EF_{grid}^{crit}:

– climatic advantage mode of the electric solution $\left(EF_{grid} < EF_{grid}^{crit}\right)$;

– climatic equivalence mode $\left(EF_{grid} = EF_{grid}^{crit}\right)$;

– climatic advantage mode of the fuel solution $\left(EF_{grid} > EF_{grid}^{crit}\right)$.

The generalized analytical expression of the critical value EF_{grid}^{crit} is given in the form

$$EF_{grid}^{crit} = \frac{E_{WTW}^{fuel}}{EC}. \tag{33}$$

In the demonstration calculations, reference values of specific electricity consumption were used, which are characteristic of different types of transport:

– road transport

$$EC^{road} = 0.18 \text{ kWh}/\left(\text{t·km}\right);$$

– inland waterway transport

$$EC^{IWT} = 0.08 \text{ kWh}/\left(\text{t·km}\right);$$

– sea transport

$$EC^{sea} = 0.03 \text{ kWh}/\left(\text{t·km}\right).$$

The obtained values of the critical carbon intensity of the electricity grid when compared with the LNG solution were:

– for road transport

$$EF_{grid}^{crit,LNG,road} = \frac{105}{0.18} \approx 583 \text{ gCO}_2\text{e/kWh};$$

– for inland waterway transport

$$EF_{grid}^{crit,LNG,IWT} = \frac{50}{0.08} = 625 \text{ gCO}_2\text{e/kWh};$$

– for sea transport

$$EF_{grid}^{crit,LNG,sea} = \frac{20}{0.03} \approx 667 \text{ gCO}_2\text{e/kWh}.$$

Similar calculations for traditional fuel solutions yielded the following values:

– for road transport:

$$EF_{grid}^{crit,conv,road} = \frac{95}{0.18} \approx 528 \text{ gCO}_2\text{e/kWh};$$

– for inland waterway transport:

$$EF_{grid}^{crit,conv,IWT} = \frac{45}{0.08} = 563 \text{ gCO}_2\text{e/kWh};$$

– for sea transport:

$$EF_{grid}^{crit,conv,sea} = \frac{18}{0.03} = 600 \text{ gCO}_2\text{e/kWh}.$$

Within the WTW approach, the climate feasibility of an electrical solution is formalized as a condition

$$EF_{grid} < EF_{grid}^{crit}. \tag{34}$$

The obtained relations (29) to (34) analytically confirmed the threshold nature of the climatic feasibility of electric energy solutions, according to which their advantage is not invariant, but is determined by the parameters of the energy chain, in particular the carbon intensity of the electric energy system

5. 3. Parametric stability of the results of climatic comparability

The key analytical indicator of the parametric analysis was the climatic comparability function $\Delta_{A,B}$, which determines the relative climatic feasibility of alternative energy solutions

$$\Delta_{A,B} = E_{WTW}^{A} - E_{WTW}^{B}. \tag{35}$$

In the case of comparing electric and fuel solutions, the climate comparability function is given as

$$\Delta_{el,fuel} = EC \cdot EF_{grid} - \left(E_{WTT}^{fuel} + E_{TTW}^{fuel} + E_{spec}^{fuel}\right). \tag{36}$$

The analytical sensitivity of the result to the variation of the parameters of the energy chain is given in the form of the complete differential of the corresponding function $\Delta_{A,B}$

$$\begin{aligned} d\Delta = {} & \frac{\partial \Delta}{\partial EF_{grid}} dEF_{grid} + \frac{\partial \Delta}{\partial EC} dEC - \\ & - \left(\frac{\partial \Delta}{\partial E_{WTT}^{fuel}} dE_{WTT}^{fuel} + \frac{\partial \Delta}{\partial E_{TTW}^{fuel}} dE_{TTW}^{fuel} + \frac{\partial \Delta}{\partial E_{spec}^{fuel}} dE_{spec}^{fuel} \right). \end{aligned} \tag{37}$$

From expression (36) the following partial derivatives are analytically obtained:

$$\frac{\partial \Delta}{\partial EF_{grid}} = EC, \quad \frac{\partial \Delta}{\partial EC} = EF_{grid},$$

$$\frac{\partial \Delta}{\partial E_{WTT}^{fuel}} = \frac{\partial \Delta}{\partial E_{TTW}^{fuel}} = \frac{\partial \Delta}{\partial E_{spec}^{fuel}} = -1. \tag{38}$$

As a result of the parametric analysis, it was found that the climate comparability of alternative energy solutions is parametrically unstable: the variation of key parameters of the energy chain (EF_{grid}, EC, E_{WTT}, E_{TTW}, as well as methane slip emissions) leads not only to a change in the value of the function $\Delta_{A,B}$, but also to an inversion of its sign. This means that the climate advantage of an alternative energy solution is not an invariant characteristic but is determined by the configuration of the parameters of the energy chain.

Demonstration calculations for road, inland waterway, and sea transport showed that the degree of parametric stability of the results differs significantly depending on the type of transport system. It was found that for road transport the relative advantage of traditional fuels is characterized by increased parametric stability, while for inland waterway and sea transport the results demonstrate a significantly higher sensitivity to the variation of the parameters of the energy chain.

It is shown that even a moderate variation of the upstream component or the value of methane slip emissions can lead to an inversion of the sign of the function $\varDelta_{A,B}$, that is, a change in the conclusion regarding the climatic feasibility of the alternatives.

An analytical study of parametric stability was performed on the example of comparing traditional fuel and LNG solutions. Climatic comparability is defined as

$$\varDelta_{conv,LNG} = E_{WTW}^{conv} - E_{WTW}^{LNG}. \tag{39}$$

Taking into account the structure of full-cycle emissions:

$$E_{WTW}^{LNG} = E_{WTT}^{LNG} + E_{TTW}^{LNG} + E_{slip}^{LNG}, \tag{40}$$

$$\varDelta_{conv,LNG} = \left(E_{WTT}^{conv} + E_{TTW}^{conv}\right) - \left(E_{WTT}^{LNG} + E_{TTW}^{LNG} + E_{slip}^{LNG}\right). \tag{41}$$

For a formalized assessment of parametric stability, a parameter p is introduced, which characterizes the relative reduction of the system component of the LNG solution (for example, $p = 0.10$ or $p = 0.20$)

$$E_{WTT}^{LNG} + E_{slip}^{LNG} \to (1-p)\left(E_{WTT}^{LNG} + E_{slip}^{LNG}\right). \tag{42}$$

Then

$$\varDelta_p = \varDelta_{conv,LNG} + p\left(E_{WTT}^{LNG} + E_{slip}^{LNG}\right). \tag{43}$$

The threshold condition for the transition to climate equivalence or WTW advantage of the LNG solution is given as

$$\varDelta_p \geq 0, \tag{44}$$

From here, the critical value of the parameter of reduction of the system component of the LNG solution was analytically obtained:

$$p_{crit} = \frac{-\varDelta_{conv,LNG}}{E_{WTT}^{LNG} + E_{slip}^{LNG}}, \quad \varDelta_{conv,LNG} < 0. \tag{45}$$

Demonstration results.

For road transport, it was found that achieving the WTW advantage of the LNG solution required a reduction in the system component of approximately 40%, which indicates a high parametric stability of the advantage of traditional fuel:

$$E_{WTW}^{conv} = 95\,\mathrm{gCO^2e}/\left(\mathrm{t{\cdot}km}\right),$$

$$E_{WTW}^{LNG} = 105\,\mathrm{gCO_2e}/\left(\mathrm{t \cdot km}\right),$$

$$\varDelta_{conv,LNG} = 95 - 105 = -10.$$

Under condition $E_{WTT}^{LNG} = 20$ and $E_{slip}^{LNG} = 5$ we obtained

$$p_{crit} = \frac{10}{25} = 0.40.$$

This means that even significant changes in the parameters of the LNG chain do not lead to an inversion of the $\varDelta_{A,B}$ sign.

For inland waterway transport, a reduction in the system component of the LNG solution of about 20% turned out to be sufficient to achieve climate equivalence of the alternatives:

$$E_{WTW}^{conv} = 45, \quad E_{WTW}^{LNG} = 50,$$

$$\varDelta_{conv,LNG} = 45 - 50 = -5.$$

Under condition $E_{WTT}^{LNG} = 15$ and $E_{slip}^{LNG} = 10$ we obtained:

$$p_{crit} = \frac{5}{25} = 0.20.$$

For maritime transport, it is shown that even a moderate decrease in the upstream component and methane slip emissions leads to a change in the sign of the function $\varDelta_{A,B}$, which analytically confirms the threshold nature of the results:

$$E_{WTW}^{conv} = 18, \quad E_{WTW}^{LNG} = 20,$$

$$\varDelta_{conv,LNG} = 18 - 20 = -2.$$

Under condition $E_{WTT}^{LNG} = 6$ and $E_{slip}^{LNG} = 4$ we obtained

$$p_{crit} = \frac{2}{10} = 0.20.$$

Thus, it was established that the parametric stability of the WTW comparison results has a differentiated nature depending on the type of transport: for road transport, the advantage of traditional fuels is relatively stable, while for inland waterway and maritime transport it is significantly more sensitive to the variation of the energy chain parameters.

The calculation results are summarized in Table 1, which allowed us to quantitatively illustrate the differentiated nature of parametric stability for different transport systems.

The data in Table 1 indicate that in all considered transport systems, traditional fuel solutions are characterized by a lower full-cycle climate impact compared to LNG solutions. At the same time, it was established that the threshold conditions for achieving climate competitiveness of electric solutions are less stringent when compared with LNG than with traditional fuels, which leads to a faster achievement of their climate feasibility in the first case.

It is shown that the nature of climate comparability is determined not only by the absolute values of full-cycle emissions but also by the structure of threshold conditions for electrification, which is differentially manifested depending on the type of transport. An inverse dependence of critical electrification parameters on specific energy consumption has been established: with a decrease in the energy intensity of transport work, the permissible level of carbon intensity of the power grid increases.

Our results also confirmed the differentiated nature of parametric stability: for road transport it is higher, while for inland waterway and maritime transport there is an increased sensitivity to the variation of energy chain parameters. The revealed parametric instability of the results indicates the direct impact of the choice of assessment boundaries and energy chain parameters on the formation of investment conclusions, which necessitates their further formalization.

Table 1

Demonstration values of WTW indicators and EF_{grid}^{crit} threshold values for different modes of transport

Type of transport	WTW indicators and thresholds of EF_{grid}^{crit}					The nature of ratio of indicators
	E_{WTW}^{conv}, gCO$_2$e/(t·km)	E_{WTW}^{LNG}, gCO$_2$e/(t·km)	EC, kWh/(t·km)	$EF_{grid}^{crit,LNG}$, gCO$_2$e/kWh	$EF_{grid}^{crit,conv}$, gCO$_2$e/kWh	
Automotive	95	105	0.18	583	528	$E_{WTW}^{conv} < E_{WTW}^{LNG}$, $EF_{grid}^{crit,LNG} > EF_{grid}^{crit,conv}$, which indicates the climate advantage of traditional fuels over LNG and the stricter threshold conditions for electrification when compared to traditional fuels than when compared to the LNG solution
Inland waterway	45	50	0.08	625	563	$E_{WTW}^{conv} < E_{WTW}^{LNG}$, $EF_{grid}^{crit,LNG} > EF_{grid}^{crit,conv}$, which indicates the absence of a climate advantage for LNG and that electrification achieves climate competitiveness relative to LNG under less stringent conditions than relative to traditional fuels
Marine	18	20	0.03	667	600	$E_{WTW}^{conv} < E_{WTW}^{LNG}$, $EF_{grid}^{crit,LNG} > EF_{grid}^{crit,conv}$, indicating the lack of a climate advantage of LNG and the relatively more favorable threshold conditions for electrification when compared with LNG than with traditional fuels

5. 4. Manifestation of investment asymmetry of decarbonization

To formalize the investment asymmetry of decarbonization, which arises as a result of the choice of the boundaries of the system for assessing the climate impact of alternative energy solutions, the study introduces a system of interconnected analytical indicators that reflects a sequential transition from methodological differences in assessment to their investment consequences.

Within the proposed approach, alternative energy solutions *i* and the baseline solution *b* were considered, relative to which the decarbonization benefit was assessed. The choice of the baseline solution was determined by the formulation of the comparison problem.

Within the proposed approach, the following were consistently determined:

1. Methodological gap between TTW and WTW

$$\Delta E^i = E_{WTW}^i - E_{TTW}^i, \tag{46}$$

where E_{WTW}^i and E_{TTW}^i – specific emissions of alternative solution *i*, determined respectively within the WTW- and TTW-approaches, gCO$_2$e/(t·km).

2. Decarbonization benefit of alternative solution relative to the baseline

$$B_i^k = E_b^k - E_i^k, k \in TTW, WTW. \tag{47}$$

where B_i^k – decarbonization benefit of alternative *i* within the framework of evaluation system *k*;

E_b^k – specific emissions of the baseline solution within the framework of system *k*;

E_i^k – specific emissions of the alternative solution within the framework of system *k*.

3. Decarbonization Investment Asymmetry Index (DIAI)

$$I_i = B_i^{TTW} - B_i^{WTW}, \tag{48}$$

where I_i is the decarbonization investment asymmetry index for alternative energy solution *i*.

4. Normalized form of the index.

To ensure comparability of results between different alternatives, a normalized form of the index is used

$$I_i^{norm} = \frac{B_i^{TTW} - B_i^{WTW}}{B_i^{WTW}}, \tag{49}$$

where I_i^{norm} – normalized index of investment asymmetry of decarbonization.

5. Generalized system of indicators.

Within the framework of the proposed approach, a system of interconnected analytical indicators has been formed for assessing the climate comparability of alternative energy solutions and the related investment consequences of decarbonization of energy solutions in transport systems.

The system includes:

- indicator of the methodological gap between the TTW and WTW approaches – ΔE^i;
- indicator of the decarbonization benefit of the alternative solution relative to the baseline – B_i^k;
- index of investment asymmetry of decarbonization (*DIAI*) – I_i;
- normalized form of this index – I_i^{norm}.

In the logic of the proposed model of climate comparability of alternative energy solutions (WTW Climate Comparability Model, WTW-CCM), these indicators have formed a coherent analytical chain of assessment

$$\text{Ä}E^i \rightarrow B_i^k \rightarrow I_i \rightarrow I_i^{norm}. \tag{50}$$

The logic of the relationship of indicators is shown in Fig. 1.

The formed analytical chain reflects the logic of the transition:

- from fixing the methodological gap between TTW and WTW;
- to assessing the decarbonization benefit;
- and further – to quantitative measurement of investment asymmetry.

Thus, the DIAI index is interpreted as a formalized indicator of the distortion of investment signals caused by the choice of the boundaries of the climate impact assessment system.

The developed system of indicators forms an analytical model for assessing decarbonization investment asymmetry (Analytical Model for Assessing Decarbonization Investment Asymmetry), which arises as a result of using different boundaries of the climate impact assessment system.

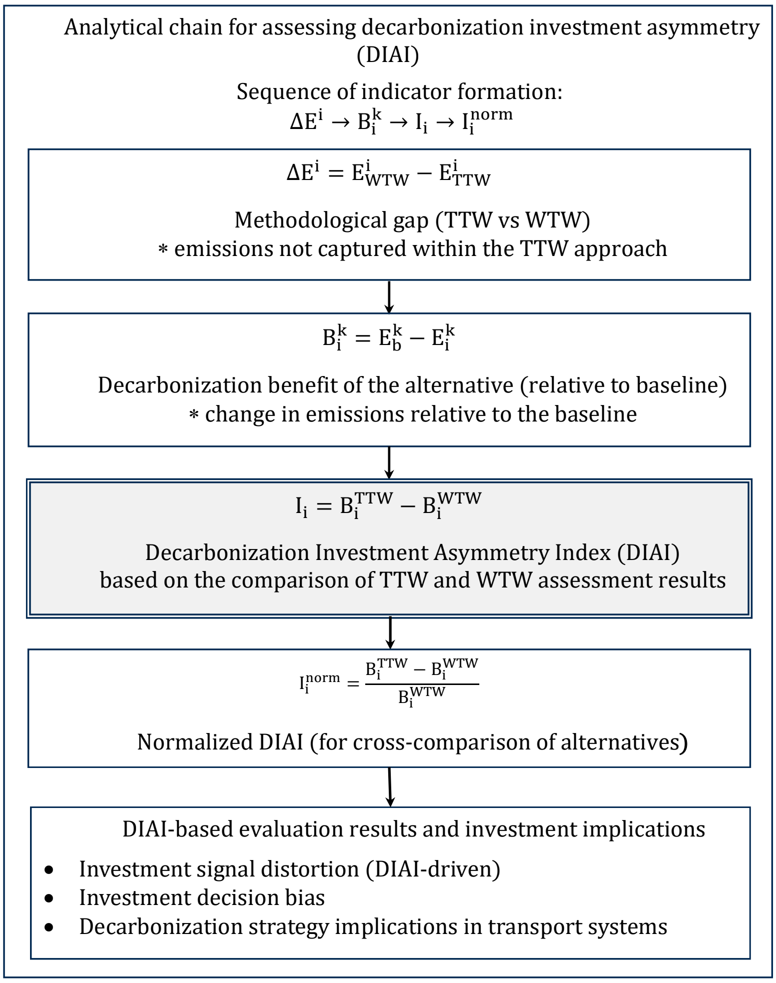

Fig. 1. Analytical structure of the indicator system and logic for forming the Decarbonization Investment Asymmetry Assessment Model (DIAI)

The proposed model expands the analytical capabilities of WTW-CCM, ensuring the transition from climate impact assessment to formalized analysis of investment consequences.

It has been established that the use of the TTW approach leads to systematic distortions in the assessment of the climate efficiency of alternative energy solutions, in particular:

– overestimation of the efficiency of technologies with low operational emissions;

– underestimation of alternatives with a significant upstream component;

– formation of distorted investment signals in the process of decarbonization of transport systems.

It is shown that these distortions are systemic in nature and directly affect the validity of strategic investment decisions.

In combination with the WTW-CCM model, the DIAI index forms an integrated analysis toolkit that allows for a coherent combination of climate impact assessment with investment impact assessment.

The key result of our study is the formalization of the investment asymmetry of decarbonization as a consequence of the choice of the boundaries of the climate impact assessment system.

The proposed approach makes it possible to interpret WTW assessment not only as a tool for accounting for full-cycle emissions but also as a basis for forming a parameterized analytical model for making investment decisions.

As a result, an integrated analytical framework was formed – the WTW Climate Comparability Framework, which combines the WTW-CCM model and the DIAI index and provides a methodological basis for substantiating investment strategies for decarbonizing transport systems.

This allows us to consider the decarbonization of transport systems as a task determined not only by the choice of technologies but also by the correctness of setting the boundaries of the climate impact assessment system.

6. Discussion of results based on investigating the climate comparability of energy solutions in transport systems

Our results showed that the use of the Tank-to-Wheel approach was insufficient for the correct assessment of the climate efficiency of energy solutions since it did not take into account the upstream components of the energy chain. This was confirmed by the analytical structure of full-cycle emissions (3), in which the inclusion of Well-to-Tank components and specific components led to a change in the results of the comparison of alternatives.

The key result was the formalization of climate comparability in the form of a function (17), which determined the preference of alternatives depending on full-cycle emissions. Unlike existing approaches [6–8], in which the results were mainly scenario-based, the use of function (17) provided an analytical definition of the conditions for changing the climate preference of alternatives, which was due to the parameterized representation of the components of the energy chain.

The results obtained for LNG solutions were determined by the structure of expressions (4) to (8), within which the methane component was distinguished as a separate component. Its explicit inclusion led to the absence of a guaranteed climate advantage of LNG, which distinguished our results from approaches in which methane slip emissions were not taken into account or were taken into account in an aggregated manner.

The threshold nature of the climatic feasibility of electrification was justified by the relation (21) and the analytical criterion (31). Unlike approaches in which electrification was considered as a priori more environmentally friendly solution, the obtained criterion (31) reflected its dependence on the parameters of the power system, which was explained by taking into account upstream electricity emissions.

Parametric analysis performed on the basis of function (17) showed the possibility of changing the sign of the $\Delta_{A,B}$ function when varying the parameters, which indicated parametric instability of the results. This allowed us to interpret the contradictory results in the literature as a consequence of differences in parametric assumptions, rather than methodological errors.

The formalization of investment asymmetry was based on a comparison of results within TTW and WTW. The obtained approach provided the possibility of quantitative assessment of the distortion of investment signals, which was previously considered mainly qualitatively.

Thus, the results of our study eliminated the problem identified in Section 2 of the lack of a parameterized analytical model for WTW estimation, providing a consistent combination of the emission structure (3), the comparability function (17), and the threshold criterion (31).

The resulting WTW Climate Comparability Framework integrated the WTW-CCM model and investment asymmetry assessment, providing an analytical basis for the decarbonization of transport systems.

The practical significance of the proposed approach was the possibility of its use as an analytical tool for substantiating management, investment, and regulatory decisions in the field of decarbonization of transport systems. The proposed approach provided a transition from simplified estimates to a parameterized analytical justification of the choice of energy alternatives, taking into account the full-cycle climate impact and associated investment risks.

In particular, our results could be used for:

- assessing the feasibility of implementing alternative energy solutions;
- justifying investments in transport and energy infrastructure;
- developing decarbonization strategies at the level of enterprises, ports, and public policy;
- harmonizing transport and energy policies;
- supporting decision-making on the choice of technological alternatives.

The proposed WTW Climate Comparability Framework could be used as a basis for creating decision-support tools that provide a quantitative assessment of the climate feasibility of alternatives and related investment consequences.

The limitations of the study include:

- the use of generalized (reference) parameters of energy systems that correspond to typical conditions, but could differ for individual regional contexts;
- the focus of the model on the energy chain (WTW) without including the full life cycle of vehicles, which corresponded to the chosen analytical formulation of the study;
- the sensitivity of the results to the choice of methane slip and GWP parameters, which reflected the objective physical and methodological dependence of the WTW assessment results on the input assumptions.

The disadvantages of the study are:

- generalized analytical representation of individual components of the energy chain, which was a consequence of the parameterized approach and ensured the consistency of the model without loss of analytical correctness;
- limited level of detail of regional characteristics of energy systems, which could affect the accuracy of applied assessments under specific conditions but did not change the general analytical conclusions.

Further advancement of the study might focus on the following:

- empirical testing of the model;
- expansion of the model to the full life cycle (LCA);
- integration of economic parameters into the model;
- design of applied decision-making support tools.

The implementation of these areas allowed us to increase the applied relevance of the model, expand its analytical capabilities, and ensure its use in strategic planning tasks for the decarbonization of transport systems.

7. Conclusions

1. It has been established that the climate comparability of alternative energy solutions is formalized in the form of a parameterized analytical model (WTW Climate Comparability Model, WTW-CCM), within which full-cycle emissions are represented as an additive function of the components E_{WTT}, E_{TTW} and E_{spec}. The defining feature of such formalization is the possibility of analytical consideration of the parameters of the energy chain, which ensures consistent comparability of alternatives based on full-cycle emissions.

2. A threshold criterion for the climate feasibility of electric energy solutions was established in the form of a critical value of the carbon intensity of the electricity grid EF_{grid}^{crit}, which, unlike existing approaches, reflects the dependence of the climate efficiency of electrification on the parameters of the energy system.

3. The parametrically dependent nature of the results of climate comparability has been established, which is manifested in the possibility of inversion of the sign of the $\Delta_{A,B}$ function when varying the parameters of the energy chain. This allowed us to identify structurally stable and threshold-dependent regimes of climate efficiency of alternatives.

4. It was found that the choice of boundaries for the assessment system (TTW or WTW) leads to the emergence of investment asymmetry of decarbonization, which is manifested in the discrepancy in the estimates of the decarbonization benefits of alternatives. The formalization of this asymmetry is implemented through a system of analytical indicators ΔE^i, B_i^k, I_i, I_i^{norm} and the DIAI index, which provides a quantitative assessment of the distortion of investment signals due to the use of simplified boundaries for assessing climate impact.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Kyryllova Valeriia: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Funding acquisition; **Kyryllova Olena:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

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