



# Qayta tiklanuvchi energiya manbalari texnologiyalari uchun zamonaviy uglerod izi va hayot siklini baholash metodikalarining tahliliy sharhi hamda Markaziy Osiyo sharoitlariga moslashtirish istiqbollari

Nargiza N. Dalmuradova

PhD, Toshkent Davlat Texnika Universiteti, Toshkent, 100095, O'zbekiston; [ndalmuradova@gmail.com](mailto:ndalmuradova@gmail.com) <http://orcid.org/0000-0003-3373-1945>

**Dolzarbli:** Markaziy Osiyo sharoitlari uchun moslashtirilgan uglerod izi va hayotiy sikl tahlili metodikalariga ehtiyoj katta, biroq mavjud CF/LCA yondashuvlari asosan Yevropa, Shimoliy Amerika va Xitoy uchun ishlab chiqilgan hamda O'zbekistonga mos bo'lmagan inventar ma'lumotlar va iqlimiy farazlarga tayanadi.

**Maqsad:** Asosiy qayta tiklanuvchi energiya texnologiyalari uchun zamonaviy CF va LCA metodologiyalarini tizimlashtirish va ularning qaysi elementlari Markaziy Osiyo sharoitlariga moslashtirishi zarurligini aniqlash.

**Usullari:** 2005–2025 yillarda chop etilgan ishlar Scopus, Web of Science, Google Scholar va eLibrary bazalaridagi tadqiqotlarni PRISMA yonashuvi asosida oldindan belgilangan mezonlar bazasida tizimli tahlil amalga oshirilgan.

**Natijalar:** CF/LCA metodikalari global darajada yaxshi rivojlangan bo'lsa-da, Markaziy Osiyo uchun ularni qo'llash lokal LCI ma'lumotlarining yo'qligi, iqlimiy degradatsiya omillari va hayotiy siklning yakuniy bosqichlari yetarli hisobga olinmasligi bilan cheklanmoqda; mintaqaviy inventarlar, dinamik LCA va arid hududlar uchun iqlimga mos CF modellari ustuvor tadqiqot yo'nalishlari sifatida taklif etildi.

**Kalit so'zlar:** uglerod izi; hayotiy sikl tahlili; qayta tiklanuvchi energetika; Markaziy Osiyo; O'zbekiston; fotoelektr stansiyalar; shamol energetikasi; gidroenergetika; biomassa energiyasi; dinamik LCA.

## Аналитический обзор современных методик оценки углеродного следа и жизненного цикла для технологий возобновляемых источников энергии и перспективы их адаптации к условиям Центральной Азии

Наргиза Н. Далмурадова

PhD, Ташкентский государственный технический университет, Ташкент, 100095, Узбекистан; [ndalmuradova@gmail.com](mailto:ndalmuradova@gmail.com) <http://orcid.org/0000-0003-3373-1945>

**Актуальность:** Актуальность данного обзора обусловлена необходимостью адаптации современных методологий оценки углеродного следа и анализа жизненного цикла технологий возобновляемой энергетики к условиям Центральной Азии, поскольку существующие подходы в основном разработаны для Европы, Северной Америки и Китая и недостаточно учитывают региональные климатические, инфраструктурные и энергетические особенности.

**Цель:** систематизация современных методологий оценки углеродного следа и анализа жизненного цикла для основных технологий возобновляемой энергетики, а также в выявлении основных методологических пробелов, ограничений и перспектив их адаптации к условиям Центральной Азии.

**Методы:** В исследовании применен систематический обзор литературы на основе подхода PRISMA. Публикации за 2005–2025 гг. были собраны из основных научных баз данных Scopus, Web of Science, Google Scholar и eLibrary, отобраны в соответствии с заранее определенными критериями включения, и 54 релевантных исследования были выбраны из приблизительно 450 выявленных источников для итогового качественного анализа.

**Результаты:** Выявлены основные барьеры адаптации CF- и LCA-методологий к региональным условиям, включая отсутствие локальных LCI-данных, недостаточный учет климатических факторов деградации и ограниченное рассмотрение сценариев окончания жизненного цикла. Определены приоритетные направления дальнейших исследований.

**Ключевые слова:** углеродный след; оценка жизненного цикла; возобновляемая энергетика; Центральная Азия; Узбекистан; динамическая LCA.

**For citation:** Dalmuradova N.N. Analytical review of contemporary carbon footprint and life cycle assessment methodologies for renewable energy technologies and prospects for their adaptation to Central Asian conditions. Scientific and technical journal of Problems of Energy and Sources Saving, 2025, no 1, pp. 172-182.

<https://doi.org/10.5281/zenodo.20086157>

Received: 19.11.2025  
Revised: 15.12.2025  
Accepted: 17.02.2026  
Published: 26.03.2026

**Copyright:** © Nargiza N. Dalmuradova, 2026. Submitted to Problems of Energy and Sources Saving for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).



# Analytical review of contemporary carbon footprint and life cycle assessment methodologies for renewable energy technologies and prospects for their adaptation to Central Asian conditions

Nargiza N. Dalmuradova

PhD, Tashkent State Technical University, Tashkent, 100095, Uzbekistan; [ndalmuradova@gmail.com](mailto:ndalmuradova@gmail.com) <http://orcid.org/0000-0003-3373-1945>

**Relevance:** The review shows that CF and LCA methodologies for renewable energy technologies are globally well developed, but their regional applicability remains highly uneven, with Central Asia still underrepresented. The analysis identifies the main barriers to their transfer to regional conditions, including the absence of local life cycle inventory datasets, insufficient consideration of climatic degradation factors, and limited treatment of end-of-life scenarios. Priority research directions include the development of regional inventories, dynamic LCA approaches, and climate-adapted carbon footprint models for renewable energy systems in arid regions.

**Aim:** The aim of this review is to systematize contemporary carbon footprint and life cycle assessment methodologies for the principal renewable energy technologies and to identify the main methodological gaps, limitations, and prospects for their adaptation to the conditions of Central Asia.

**Methods:** The study applies a PRISMA-inspired systematic literature review approach. Publications from 2005–2025 were collected from major scientific databases of Scopus, Web of Science, Google Scholar, and eLibrary, screened according to predefined inclusion criteria, and 54 relevant studies were selected from approximately 450 identified sources for the final qualitative analysis.

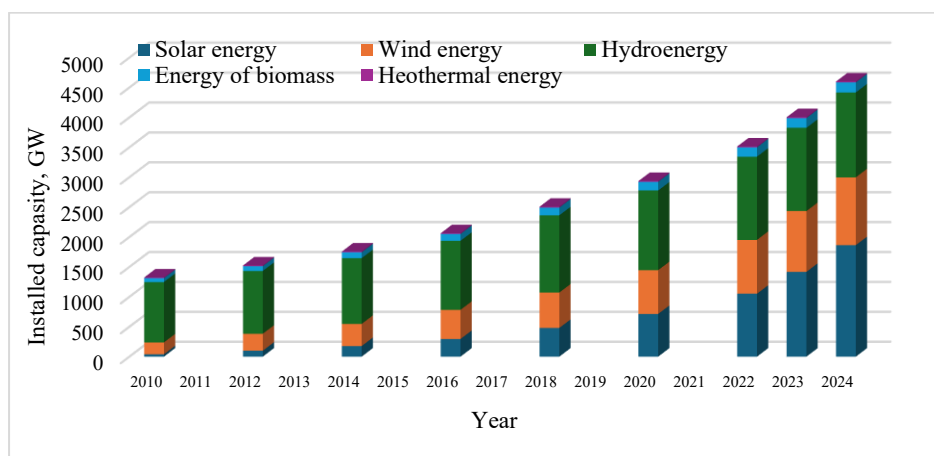
**Results:** The review shows that CF and LCA methodologies for renewable energy technologies are globally well developed, but their regional applicability remains highly uneven, with Central Asia still underrepresented. The analysis identifies the main barriers to their transfer to regional conditions, including the absence of local life cycle inventory datasets, insufficient consideration of climatic degradation factors, and limited treatment of end-of-life scenarios. The priority directions for future research include the development of regional inventories, dynamic LCA approaches, and climate-adapted carbon footprint models for renewable energy systems in arid regions.

**Keywords:** carbon footprint; life cycle assessment; renewable energy; Central Asia; Uzbekistan; photovoltaic systems; wind energy; hydropower; biomass energy; dynamic LCA.

## 1. Introduction

Global climate change remains one of the most significant challenges of our time, shaping the trajectory of international energy policy. According to the Global Carbon Budget project, global anthropogenic carbon dioxide emissions reached a record 38.1 Gt CO<sub>2</sub> in 2024 [1], demonstrating that the anthropogenic burden on the Earth's climate system continues to intensify despite commitments under the 2015 Paris Agreement to limit global warming to 1.5–2.0 °C above pre-industrial levels [2].

Renewable energy (RE) technologies are regarded by the global community as a key instrument for decarbonizing the energy sector. Total installed RE capacity worldwide reached 4,601 GW by the end of 2024 [3, 4], with approximately 600 GW of new capacity commissioned in 2024 alone – an absolute record.



**Fig.1.** Dynamics of global installed renewable energy capacities worldwide during 2010–2024, compiled by the author based on IRENA Renewable Capacity Statistics 2025 [4]

The International Renewable Energy Agency (IRENA) projects that RES capacity must triple by 2030 to achieve the Paris Agreement targets [4]. Concurrently, the International Energy Agency (IEA)



Net Zero Emissions by 2050 Scenario (NZE) underscores that renewable electricity must constitute over 60% of total generation by 2030 [5].

However, the widely held perception of RES as “carbon-neutral” technologies requires substantial qualification. While operational emissions are indeed near zero for photovoltaic (PV) power plants, wind power plants (WPP), and hydropower plants (HPP), the complete life cycle of these technologies – from raw material extraction and equipment manufacturing to transportation, installation, operation, maintenance, and decommissioning – entails appreciable greenhouse gas (GHG) emissions. The production of crystalline silicon PV modules, for instance, involves energy-intensive processes requiring 60–90 kW·h per kilogram of purified silicon [6, 7], which generates a significant “embedded” carbon footprint (CF).

In this paper, the term renewable energy (RE) is used consistently to refer to renewable energy technologies, while carbon footprint (CF) and life cycle assessment (LCA) are applied according to ISO 14067 and ISO 14040/14044 terminology.

Of fundamental importance is the geographic factor: the same PV panel installed under the high-irradiation conditions of Uzbekistan ( $GHI = 1,500\text{--}2100$  kWh/m<sup>2</sup>/yr [8]) will generate approximately twice as much electricity over its lifetime as the same system installed in Germany ( $GHI \approx 1,000$  kWh/m<sup>2</sup>/yr) [9], which proportionally reduces the specific CF per unit of energy produced. This dependency underscores the necessity of developing regionally adapted life cycle assessment (LCA) methodologies.

The Republic of Uzbekistan demonstrates one of the most dynamic trajectories of RE development in the Central Asian region. By the end of 2025, the cumulative installed capacity of PV and WPPs reached 5,582 MW [10]. Uzbekistan’s Third Nationally Determined Contribution (NDC3) envisages a 50% reduction in carbon intensity by 2035 relative to 2010 levels [11], and the National Carbon Registry will begin operations in 2026 [12], creating institutional prerequisites for the systematic application of LCA methodologies. The Carbon Neutrality Strategy to 2050 [13] further reinforces the policy framework for low-carbon development.

In Uzbekistan, a substantial research base in power engineering and RES has already been established, providing essential system, climatic, and technological parameters for regional CF-LCA applications. Existing studies have quantified the potential of RE sources across the territory of Uzbekistan, developed rational engineering solutions for solar-based power supply systems, assessed energy security indicators under renewable energy scaling, evaluated wind resources, and proposed development scenarios for RE deployment in Uzbekistan and Central Asia [8, 14–25]. These studies form a strong empirical and engineering foundation for regional life cycle modelling. However, despite this substantial research background, a comprehensive CF-LCA methodology adapted to Central Asian conditions has not yet been developed. Existing international life cycle inventory databases, including Ecoinvent and GaBi, do not contain region-specific datasets for Central Asia, while standard assumptions based on Western European conditions remain poorly applicable due to fundamentally different climatic, infrastructural, and economic conditions [26, 27].

The aim of this review is to systematize existing CF and LCA methodologies for all principal types of RE technologies – PV, WPP, HPP, energy of biomass, and hybrid systems – and to identify gaps impeding their adaptation for Central Asian conditions.

## 2. Materials and Methods

This review was conducted as a systematic literature review using a PRISMA-inspired workflow. The search for publications was carried out in the following electronic databases: Scopus, Web of Science, Google Scholar, eLibrary.ru, and ResearchGate. The search period covered 2005–2025, with emphasis on publications from the last decade (2015–2025). Search queries were formulated in Russian and English and included the following key terms and their combinations: “life cycle assessment of RE”, “carbon footprint of PV”, “carbon footprint of wind energy”, “LCA energy Central Asia”, “GWP of hydropower”, “LCA of biomass energy”, and their Russian-language equivalents.

Inclusion criteria: (1) peer-reviewed scientific articles published in refereed journals or conference proceedings; (2) compliance with the methodological standards ISO 14040/14044; (3) availability of quantitative data on global warming potential (GWP) or carbon footprint (CF); (4) technological relevance – consideration of one or more RES types.

Exclusion criteria: non-peer-reviewed publications, studies lacking quantitative data, and research published before 2005.

At the initial screening stage, approximately 450 publications were identified. After applying the inclusion and exclusion criteria and removing duplicates, 54 publications were included in the final analysis [1–54]. The distribution of publications across thematic blocks was performed according to the developed classification scheme (Fig. 2).

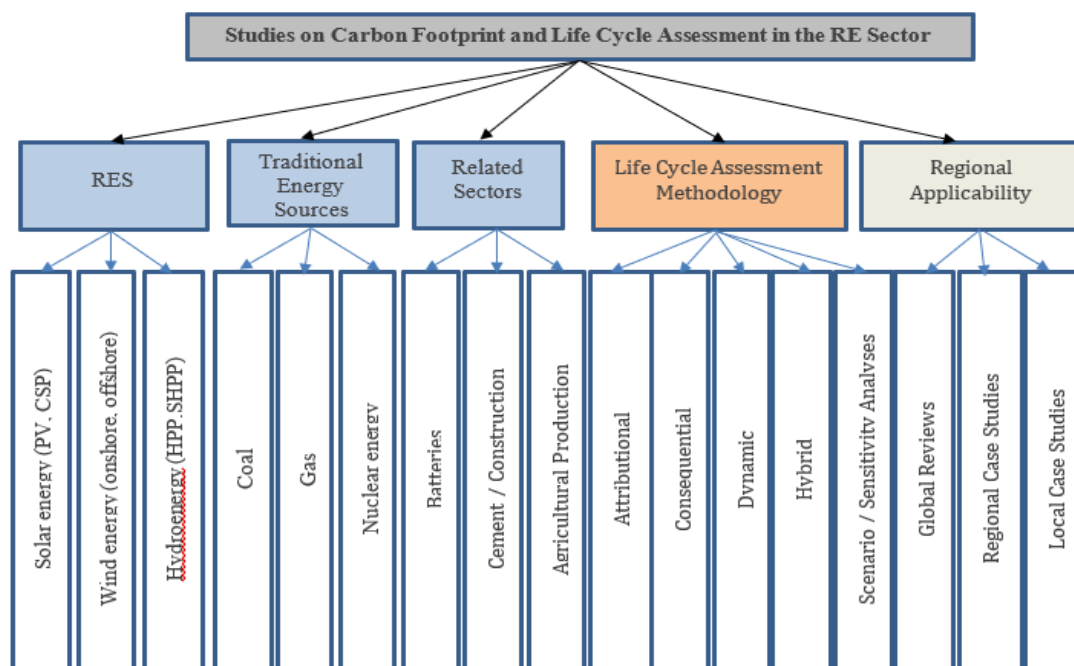


Fig. 2. Classification of CF/LCA studies in the energy sector

For the systematization of the identified literature, a five-block classification scheme for CF and LCA studies in the energy sector was developed (Fig. 2). The classification covers: (1) RE sources, including solar, wind, and hydropower; (2) traditional energy sources used as comparative benchmarks; (3) related sectors, including batteries, construction materials, and agricultural production; (4) methodological LCA approaches, including attributional, consequential, dynamic, hybrid, and scenario-based analyses; and (5) regional applicability, covering global, regional, and local case studies.

### 3. Results

#### 3.1 Methodological foundations of life cycle assessment

International standards ISO 14040:2006 [28] and ISO 14044:2006 [29] define the general principles and requirements for conducting LCA, establishing a four-phase procedure: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results. Standard ISO 14067:2018 [30] specifies requirements for the quantitative determination of the CF of products based on the general LCA methodology.

The definition of system boundaries constitutes a critical methodological decision that substantially affects results. In the energy sector, the most widely adopted approach is “cradle-to-grave” analysis, encompassing the stages of raw material extraction, equipment manufacturing, transportation, construction, operation, maintenance, and decommissioning [6, 26].

Three principal methodological approaches are widely used in life cycle assessment (LCA) practice. Attributional LCA (A-LCA) uses average data on existing processes to describe the system in a static state and assess the impact of the product under consideration under current conditions. Consequential LCA (C-LCA) models marginal changes in the system arising from a particular decision and assesses changes in total system impact when production increases or decreases [31-33]. Dynamic LCA (d-LCA) integrates temporal changes in system parameters – such as technological development, grid decarbonization, and equipment degradation – within the LCA framework [34]. Comparative studies show that attributional LCA based on static average grid emission factors may overestimate the lifetime carbon footprint of new PV systems by 25–40% compared with dynamic LCA approaches, particularly in rapidly decarbonizing power systems. Similar effects are reported for wind energy projects, where future reductions in manufacturing-related emissions and grid decarbonization significantly reduce long-term specific GWP values [7, 34].

In addition to these three principal approaches, hybrid methods are being developed that combine process-based LCA with economic input-output analysis, enabling system boundary expansion without significantly increasing the complexity of inventory data collection [27]. Scenario analysis and sensitivity analysis are employed as standard verification tools for LCA results [6, 26].

**Table 1.** Comparison of LCA methodological approaches

Approach	System Model	Application in RES	Limitations
Attributional LCA (A-LCA) [31-33]	Static, average data	Environmental product declarations, technology comparison	Does not reflect system dynamics or decision consequences
Consequential LCA (C-LCA) [31-33]	Marginal-change modeling	Policy evaluation, capacity planning	High uncertainty of marginal processes
Dynamic LCA (d-LCA) [34]	Temporal, variable parameters	Long-term planning, accounting for grid decarbonization	Modeling complexity, limited baseline data

### 3.2 Carbon footprint of RE technologies: global research results

This subsection summarizes the global ranges of lifecycle carbon footprint values reported for the major RE technologies and highlights their possible variation under Central Asian conditions (Fig.3).

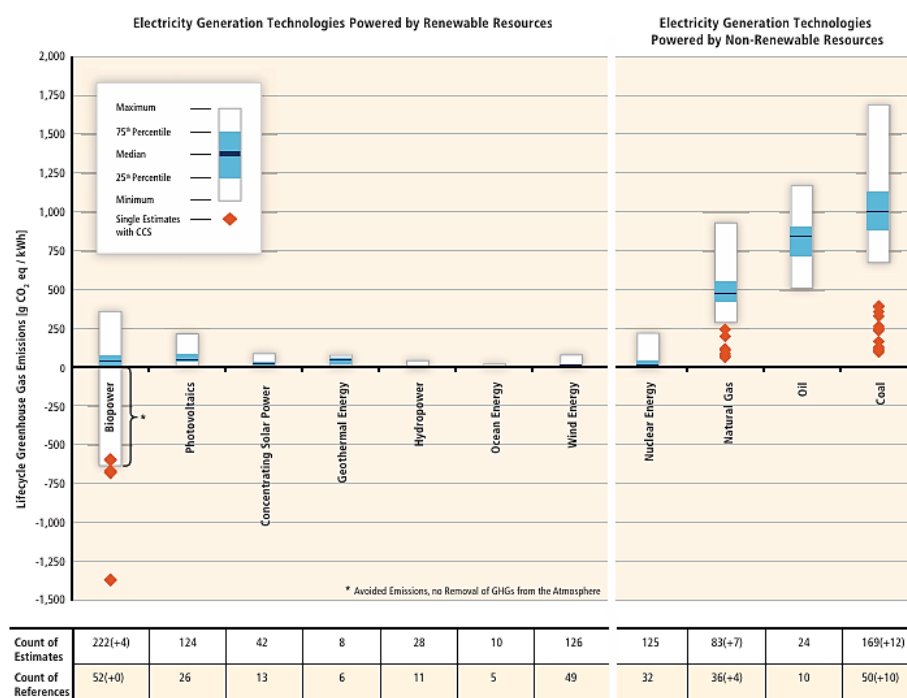
As shown in Fig. 3, RE technologies generally demonstrate substantially lower lifecycle GHG emissions than fossil-based generation, although significant variability remains across technology types and deployment conditions [35-36].

#### 3.2.1 Photovoltaic (PV) power plants

IEA PVPS Task 12 (2023) reports specific CF values of 35.8 (mono-Si), 43.6 (poly-Si), and 25.2 (CdTe) g CO<sub>2</sub>eq/kWh at GHI = 1,331 kWh/m<sup>2</sup>/yr, with the manufacturing stage accounting for 65–88% of total lifecycle GWP [37-39]. Under Uzbekistan conditions (GHI = 1,500-2,100 kWh/m<sup>2</sup>/yr [8]), the estimated CF may decrease to approximately 21–28 g CO<sub>2</sub>eq/kWh, with an energy payback time of 0.8–1.2 years [40].

#### 3.2.2 Wind power plants

NREL (2022) established median GWP of 11 g CO<sub>2</sub>eq/kWh (7–45) for onshore and 12 g (8–23) for offshore wind [41]. Manufacturing (tower, nacelle, rotor) accounts for 72–85% of lifecycle GWP. Turbine capacity growth from 1.6 MW (2010) to 4.5–6 MW (2024) has progressively reduced specific CF. For Uzbekistan, regional assessments [22, 42] reported wind speeds of 6.5–9.0 m/s at 100 m in Karakalpakstan, which may contribute to lower lifecycle CF through higher electricity yield.



**Fig. 3.** Harmonized lifecycle greenhouse gas emission ranges for major electricity generation technologies (g CO<sub>2</sub>eq/kWh), adapted by the author from IPCC SRREN Figure SPM.8 [36]

#### 3.2.3 Hydropower (HPP and SHPP)

Run-of-river HPP exhibit a median GWP of 4 g CO<sub>2</sub>eq/kWh (1–22), while reservoir-type facilities may reach 147 g CO<sub>2</sub>eq/kWh due to methane emissions from submerged organic matter. The long operational lifespan (50–80 years) dilutes the construction-stage carbon burden over time. In Uzbekistan, existing capacity totals 4,093 MW (large and small HPP combined); transboundary water constraints limit new development, making LCA-based comparison with solar and wind alternatives



particularly relevant [6, 43].

#### 3.2.4 Biomass energy

IPCC AR6 reports a median GWP of 230 g CO<sub>2</sub>eq/kWh (45–1,500) for direct combustion; BECCS can yield net-negative values down to –1,050 g CO<sub>2</sub>eq/kWh [6]. Supply chain emissions contribute 40–60% of total lifecycle GWP for agricultural residues. Agricultural residues, including cotton husks and rice straw, may represent a relevant local feedstock base in Uzbekistan [44].

#### 3.2.5 Hybrid systems

Hybrid system CF is calculated as the weighted sum of component contributions plus storage. Li-ion batteries add 20–50 g CO<sub>2</sub>eq/kWh per delivered kWh of stored electricity [45], with carbon footprint allocation across components remaining the key methodological challenge. In Uzbekistan, 1,245 MW of battery storage was commissioned in 2025, creating demand for dedicated LCA protocols covering battery degradation in extreme temperatures and end-of-life recycling – areas currently absent from regional frameworks.

### 3.3 Regional studies: global experience and Central Asia

The geographic distribution of LCA studies on RES remains strongly asymmetric: most research is concentrated in Western Europe, North America, and China, while Central Asia is still weakly represented (Table 2). Nevertheless, a growing regional evidence base has emerged, covering the covering RE potential across Uzbekistan, solar-based engineering solutions, energy security under RES scaling, wind resource assessment, regional feasibility studies, and environmental implications under arid conditions [14-25].

These studies, although not strict ISO-based LCA analyses, provide the critical regional input parameters required for lifecycle modelling, including irradiation levels, wind capacity factors, deployment scenarios, environmental constraints, and long-term energy transition pathways. In the international context, the benchmark methodological references remain the global integrated LCA review of electricity systems [46], the regionalized electricity inventories of Ecoinvent [47-48], and the harmonized PV LCA framework developed under IEA PVPS Task 12 [49], which together form the methodological basis for future Central Asia-specific LCA studies.

**Table 2. Regional and benchmark studies relevant to CF-LCA of renewable energy systems with focus on Central Asia**

Authors	Year	Country/ Region	Technology	LCA Method	GWP, g CO <sub>2</sub> eq/ kWh	Key Findings
Hertwich E. et al. [35]	2015	Global	RES, thermal	A-LCA	4–820	Aggregate GHG emissions of global power system scenarios were quantified.
Fthenakis V. et al. [38]	2011	Global	Solar PV	Harmonized LCA	20–80	Harmonized PV-LCA data under IEA PVPS Task 12 were established.
Kadiyala A. et al. [43]	2016	Global	Hydro	LCA meta- analysis	4(1– 147)	GWP values for low-carbon electricity benchmarks were systematised across hydropower types.
Treyer K., Bauer C. [47]	2013	Europe	Power grid	A-LCA / ecoinvent	-	Regional adaptation of LCA databases for electricity-sector modelling was demonstrated.
Allayev K.R. [50-51]	2000– 2021	Uzbekistan	Power system / RES integration	Indicator analysis	-	Foundational system-level studies on the structure, reliability and efficiency of the national power system; provides conceptual basis for subsequent RES integration and CF/LCA studies.
Avezov R.R. et al. [8]	2012	Uzbekistan	Solar PV	Resource assessment	-	Technical PV potential was assessed accounting for regional irradiation around 1,500-2,100 kWh/m <sup>2</sup> /year.
Avezova	2019	Uzbekistan	RES	Techno-	-	Challenges and solutions



N.R. et al. [15-16]				economic / review		for RES development in Uzbekistan were systematised; barriers and opportunities for national RES deployment were identified.
Mirzabaev A.M., Isakov A., Soliev O. et al. [19]	2021	Uzbekistan	Solar PV	Review / trend analysis	-	Major trends of solar energy development in Uzbekistan were identified, including institutional and sectoral dynamics.
Matchanov N.A. [20]	2021	Uzbekistan	Solar PV / grid integration	Techno-economic / systems analysis	-	Comprehensive study of PV systems and their integration into the electric grid of Uzbekistan; provides system design and grid-integration parameters.
Rakhimov E.Yu. [22-23]	2021, 2026	Uzbekistan	Solar resource	Resource assessment / database verification	-	Validated methods and databases for the assessment and forecasting of solar and wind energy resources across Uzbekistan have been developed, providing reliable heliometric and wind input parameters for regional CF-LCA studies.
Avezova N.R. et al. [18]	2022	Uzbekistan	Solar PV	Systems analysis	-	Design recommendations for solar-based power-supply systems were developed for different consumer groups.
Tursunov M.N., Yuldashev I.A. et al. [24-25]	2007–2023	Uzbekistan	Photovoltaic and photothermal systems	Experimental studies	-	Investigations of PV modules, PVT converters and hybrid systems in dry climate conditions provide component-level parameters for RES life cycle inventories.
Khanam T., Kiggundu-Musoke M.G., Madaminov M. et al. [44]	2021	Central Asia	Multi-RES	Review	-	Regional overview of RES potential, deployment barriers and future outlook in Central Asia.
Bijanov A., Ktaybekov M., Mamutov M., Saparova U. [42]	2025	Karakalpakstan	Wind	Resource assessment	-	Technical feasibility of wind deployment in north-western Uzbekistan was confirmed, including promising siting zones.

## 4. Discussion

### 4.1 Analysis of methodological gaps

The systematic review conducted allows the identification of five key methodological gaps limiting the application of LCA for assessing the CF of RES technologies under Central Asian conditions.

Gap 1: Absence of Central Asian LCI data. None of the leading LCA databases contains regional data for Central Asian countries. The consequence is the forced use of European and American proxy data, which introduces a systematic error estimated at 15–30% for CF calculations. This error stems from differences in the carbon intensity of electricity grids (Uzbekistan: ~500 g CO<sub>2</sub>/kWh vs. the European average of ~250 g CO<sub>2</sub>/kWh), transport distances, and industrial processes [47, 48, 52].

For Central Asia, the priority parameters requiring regionalization include: (1) the carbon intensity



of the national electricity mix used during manufacturing and auxiliary consumption; (2) transport distances and logistics routes for imported PV modules, wind turbines, and battery systems; (3) climate-specific degradation factors such as dust soiling, extreme temperatures, and seasonal thermal stress affecting PV and battery performance; and (4) end-of-life scenarios, including collection systems, recycling availability, and disposal practices under limited regional waste-management infrastructure.

Gap 2: Static LCA models for dynamic systems. Under conditions of rapid decarbonization of the Uzbekistan energy system, attributional LCA based on current average data overestimates the CF of new RES installations over their life cycle (25 years) by up to 40%. This is because the carbon intensity of the grid used for manufacturing replacement equipment and auxiliary needs will progressively decline [7, 34].

Gap 3: End-of-life stage not addressed. By 2030, Uzbekistan will have solar power plants with a cumulative capacity of approximately 5 GW requiring decommissioning planning. Currently, no LCA methodology exists for PV module disposal under arid climate conditions, nor is there a regulatory framework for RES waste management in the region. The EU experience (Waste Electrical and Electronic Equipment Directive) cannot be mechanically transferred to Central Asian conditions given differences in recycling infrastructure [6]. In practice, the region also faces serious infrastructural constraints: there are no specialized industrial enterprises for processing photovoltaic waste, reverse logistics chains for collecting modules remain undeveloped, and there are still no officially established mechanisms for manufacturers' responsibility for photovoltaic waste. Recycling of batteries is further hampered by the requirements for handling hazardous materials and insufficient technological capabilities.

Gap 4: Climate factors not incorporated. Peer-reviewed studies confirm that dust soiling under desert conditions reduces output by 2–5% daily, while extreme temperatures (up to +47 °C) additionally reduce performance by 7–8%. These factors directly affect the denominator of the specific GWP indicator (kWh of energy produced) and consequently increase the calculated CF. Standard LCA models calibrated for the temperate climate of Western Europe do not account for these factors [8, 21, 53].

Gap 5: LCA not integrated with multi-criteria analysis. The review confirms the finding by Strantzali and Aravossis (2016) [54] that only 12% of RES studies integrate LCA environmental indicators into multi-criteria analytical frameworks. Sound decision-making regarding RES technology selection requires simultaneous consideration of environmental (CF), economic (levelized cost of electricity), technical (capacity utilization factor), and social (job creation, land use) criteria [55-56].

#### 4.2 International comparison and future research directions

The methodological maturity of LCA research on RE systems varies substantially across regions. Developed economies, including the European Union and the United States, possess extensive harmonized studies, mandatory environmental product declarations, and specialized databases such as Ecoinvent and NETL [47, 57-58]. China has established the national standard GB/T 39793-2021 for PV module LCA [59], while India has introduced national CF guidelines within the National Solar Mission framework [1]. In contrast, Central Asia remains characterized by the absence of mandatory LCA requirements, the lack of a regional LCI database, and a limited number of original studies. This methodological gap becomes critically important in the context of the planned launch of the National Carbon Registry of Uzbekistan in 2026 [12], where carbon credit verification will require regionally adapted and methodologically robust CF data.

Comparative analysis demonstrates the strong geographic dependency of renewable energy CF values: for solar PV, the transition from Germany (GHI 1,000 kWh/m<sup>2</sup>/year) to Uzbekistan (GHI 1,500-2,100 kWh/m<sup>2</sup>/year) may reduce specific CF by approximately 44% solely due to increased energy yield, while a similar relationship is observed in wind energy through higher regional capacity factors [8, 9, 61-62]. These findings define the principal future research priorities for Central Asia: the development of a regional LCI database, the application of dynamic LCA for a rapidly transforming electricity mix, the integration of climate-specific degradation factors such as dust, extreme temperatures, and UV stress, and the harmonization of end-of-life scenarios under arid-zone recycling conditions [46].

At the same time, the Central Asian context is characterized not by the absence of primary renewable energy research, but by the lack of its systematic integration into CF-LCA frameworks. In Uzbekistan, existing studies already provide detailed information on power system structure, solar and wind resource distributions, and the performance of PV, PVT, and small-scale renewable energy systems. Translating this empirical evidence into harmonized regional life cycle inventory datasets and dynamic CF-LCA models therefore represents a key near-term research priority, directly supporting the implementation of Uzbekistan's National Carbon Registry and broader low-carbon development strategies.



## 5. Conclusions

This systematic review confirms that CF-LCA methodologies for RES are globally mature, but Central Asia remains critically underrepresented in international life cycle inventory databases. For Uzbekistan, the absence of local LCI datasets introduces systematic uncertainties and limits the reliability of regional carbon accounting. The reviewed studies show that the manufacturing stage is the dominant lifecycle contributor, while regional climatic factors, such as including high solar irradiation, dust loading, and extreme temperatures – significantly modify LCA outcomes. In this context, the launch of the National Carbon Registry of Uzbekistan by 1 January 2026 [12] creates an urgent need for a standardized and region-adapted CF-LCA protocol. The key future priorities are the development of a Central Asian regional LCI database, the application of dynamic LCA, and the integration of climate-specific degradation and end-of-life factors for arid-zone RES.

A particularly promising direction for future research is the integration of CF-LCA outputs into multi-criteria decision-making frameworks such as AHP, TOPSIS, and VIKOR for technology selection under Central Asian conditions. This would enable simultaneous consideration of carbon footprint, electricity cost, climatic degradation, grid integration, and socio-economic impacts, thereby supporting more robust policy and investment decisions for RE deployment.

## References

1. Pierre Friedlingstein, Michael O'Sullivan, Matthew W. Jones, et al., IN: Earth System Science Data (Preprint), <https://essd.copernicus.org/preprints/essd-2025-659/>.
2. UNFCCC. Paris Agreement. Bonn: United Nations Framework Convention on Climate Change, 2015. [https://unfccc.int/sites/default/files/resource/parisagreement\\_publication.pdf](https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf).
3. IEA. World Energy Transitions Outlook 2025.2025, 519 p. <https://iea.blob.core.windows.net/assets/9753df19-0a71-422a-b725-012c555763b3/WorldEnergyOutlook2025.pdf>
4. IRENA. Renewable Capacity Highlights 2025.4 p. [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Mar/IRENA\\_DAT\\_RE\\_Capacity\\_Highlights\\_2025.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Mar/IRENA_DAT_RE_Capacity_Highlights_2025.pdf)
5. IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris: International Energy Agency, 2023, 224 p. [https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector\\_CORR.pdf](https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf)
6. IPCC. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report / eds. P.R. Shukla et al. Cambridge: Cambridge University Press, 2022, 2913 p. <https://doi.org/10.1017/9781009157926>.
7. Collinge, W.O., Landis, A.E., Jones, A.K. et al. Dynamic life cycle assessment: framework and application to an institutional building. *Int J Life Cycle Assess* 18, 538–552 (2013). <https://doi.org/10.1007/s11367-012-0528-2>
8. Avezov, R.R. and et all. History and State of Solar Engineering in Uzbekistan. *Applied Solar Energy*. -2012. Vol. 48. - No. 1. - P. 14-19.
9. Solargis. Solar resource maps of Germany. Global Horizontal Irradiation. Available at: <https://solargis.com/resources/free-maps-and-gis-data?locality=germany>
10. Ministry of Energy of the Republic of Uzbekistan. Results of electricity and RES development in 2025. Tashkent, 2025.
11. Republic of Uzbekistan. Updated Nationally Determined Contribution (NDC 3.0) for the period up to 2035. Tashkent, 2025. Available at: <https://unfccc.int/sites/default/files/2025-11/Uzbekistan%20Third%20NDC.pdf>
12. Presidential Decree No. PD–110 “On Measures for Participation in the International Carbon Units Market”. <https://lex.uz/ru/docs/7616216>
13. Scenarios for achieving carbon neutrality in Uzbekistan. Tashkent, 2023. <https://imrs.uz/public/ckfinder/userfiles/files/test/%D0%A0%D1%83%D1%81%20%D0%9D%D0%B5%D0%B9%D1%82%D1%80%D0%B0%D0%BB%D1%8C%D0%BD%D0%BE%D1%81%D1%82%D1%8C.pdf>
14. Allaev, K.R., Avezova, N.R., Zoryna, T.G., Dalmuradova, N.N. On the Issue of Choosing Indicators of Energy Security of the Republic of Uzbekistan in the Context of Scaling Renewable Energy // *Applied Solar Energy*, 2024, Vol. 60, No. 3, P. 638–661. <https://doi.org/10.3103/S0003701X2460262X>
15. Avezova, N.R., Vokhidov, A.U., Farmonov, A.A., Dalmuradova, N.N. Renewable Energy: Challenges and Solutions // *Applied Solar Energy*, 2019, Vol. 55, No. 2, P. 149–152. <https://doi.org/10.3103/S0003701X1902004X>.
16. Avezova, N.R., Toshev, Zh.B., Dalmuradova, N.N. et al. Renewable Energy: Scenario and Model of Development // *Applied Solar Energy*, 2019, Vol. 55, No. 6, P. 533–543. <https://doi.org/10.3103/S0003701X19060021>
17. Avezova, N.R., Dalmuradova, N.N., Erkin Khaltursunov, Matchanov N.A. Environmental aspects



- of renewable energy development in Uzbekistan // Innovative technologies, 2020, Special Issue, P. 92–97. <https://www.researchgate.net/publication/352118512>.
18. Avezova, N.R., Rakhimov, E.Yu., Dalmuradova, N.N. et al. Selection and Justification of Rational Technical Solutions for Power Supply Systems based on Solar Energy // Applied Solar Energy, 2022, Vol. 58, No. 6, P. 1090–1101. <https://DOI:10.3103/S0003701X22060056>.
19. A Mirzabaev, A Isakov, O Soliev, M Makhkamova and D Kodirov. Major trends characterizing solar energy development in Uzbekistan // IOP Conf. Ser.: Earth Environ. Sci. 939 012010, <https://iopscience.iop.org/journal/1755-1315>
20. Matchanov N.A. Comprehensive study of photovoltaic systems and their integration into the electric grid. The abstract. diss. for the degree of Doctor of Technical Sciences, Tashkent., 2021, p.64.
21. Avezova, N.R., Rakhimov, E.Yu., Dalmuradova, N.N., Shermatova M.B. Adjustments to the indicators of the heating and cooling degree-days for regions of the Republic of Uzbekistan // IOP Conference Series Earth and Environmental Science, 939(1):012017, 2021, <https://DOI:10.1088/1755-1315/939/1/012017>.
22. Rakhimov, E.Yu., Avezova, N.R. & Jamoldinov, F.Z. Evaluation of the Gross Wind Energy Potential of Uzbekistan // Renewable Energy Research and Applications, 2023, Vol. 4, No. 1, P. 68–89. <https://energy.tdtu.uz/index.php/journal/article/view/147>
23. Raximov E.YU. Methods for assessing and forecasting the potential of solar and wind energy improvement and application in the republic of Uzbekistan. The abstract. diss. for the degree of Doctor of Technical Sciences, Fergana., 2026, p.64.
24. Tursunov M.N., Muminov R.A., Tukfatullin O.F., Yuldashev I.A., Abdullaev E.T. Photothermal Electric Battery Based on Silicon Solar Cells // Applied Solar Energy. 2011. Vol. 47. No. 1. P. 63–65.
25. Shoguchkarov S.K., Yuldashev I.A., Kudratov A.R., Jamolov T.R. A Study of the Parameters of a Combined Photo-Thermoelectric Installation under Field Conditions // Applied Solar Energy. 2020. Vol. 56. No. 2. P. 125–130. DOI: 10.3103/S0003701X20020115.
26. Göran Finnveden, et al (2009). Recent developments in Life Cycle Assessment // Journal of Environmental Management, Volume 91, Issue 1, Pages 1-21, <https://doi.org/10.1016/j.jenvman.2009.06.018>.
27. Heijungs, R., Suh, S. The Computational Structure of Life Cycle Assessment. Dordrecht: Springer, 2012, 256 p. [https://web.universiteitleiden.nl/cml/ssp/publications/2002\\_004.pdf](https://web.universiteitleiden.nl/cml/ssp/publications/2002_004.pdf)
28. ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization, 2006, 20 p. <https://www.iso.org/standard/37456.html>
29. ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. International Organization for Standardization, 2006, 46 p. <https://www.iso.org/standard/38498.html>
30. ISO 14067:2018. Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification. International Organization for Standardization, 2018, 46 p. <https://www.iso.org/standard/71206.html>
31. Schaubroeck T. (2023). Relevance of attributional and consequential life cycle assessment for society and decision support. Front Sustain.; 4:1129287. <https://doi.org/10.3389/frsus.2023.1129287>
32. Maes B, et al. (2023). Prospective consequential life cycle assessment. Renew Sustain Energy Rev.; 174:113053. <https://doi.org/10.1016/j.rser.2023.113053>
33. Weidema, B.P. et al. Attributional or consequential Life Cycle Assessment: a matter of social responsibility // Journal of Cleaner Production, 2018, Vol. 174, P. 305–314. <https://doi.org/10.1016/j.jclepro.2017.10.340>
34. Salati M, Costa AA, Silvestre JD (2025). A comprehensive review of dynamic life cycle assessment for buildings: exploring key processes and methodologies. Sustainability.17(1):159. <https://doi.org/10.3390/su17010159>
35. E.G. Hertwich et al (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies, Proc. Natl. Acad. Sci. U.S.A. 112 (20) 6277–6282, <https://doi.org/10.1073/pnas.1312753111>
36. IPCC. Renewable energy sources and climate change mitigation. 2012. 246 p. [https://www.ipcc.ch/site/assets/uploads/2018/03/SRREN\\_FD\\_SPM\\_final-1.pdf](https://www.ipcc.ch/site/assets/uploads/2018/03/SRREN_FD_SPM_final-1.pdf)
37. Frischknecht, R. et al. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems / IEA PVPS Task 12, Report T12-19:2023. Paris: IEA, 2020, 89 p. <https://research-hub.nlr.gov/en/publications/life-cycle-inventories-and-life-cycle-assessments-of-photovoltaic-2/>
38. Fthenakis, V.M. et al. Life cycle inventories and life cycle assessment of photovoltaic systems / IEA PVPS Task 12. Paris: IEA, 2011, 62 p. <https://iea-pvps.org/key-topics/life-cycle-inventories-and-life-cycle-assessments-of-photovoltaic-systems/>
39. Raugei, M., Fullana-i-Palmer, P., Fthenakis, V. The energy return on energy investment (EROI) of photovoltaics // Energy Policy, 2012, Vol. 45, P. 576–582. <https://doi.org/10.1016/j.enpol.2012.03.008>
40. Solargis. Global Solar Atlas: Uzbekistan. Available at: <https://globalsolaratlas.info/download/uzbekistan>



41. Dolan, S.L., Heath, G.A. Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization // *Journal of Industrial Ecology*. 2012. Vol. 16, Suppl. 1. P. S136–S154. <https://DOI:10.1111/j.1530-9290.2012.00464.x>.
42. Alibek Bijanov, Miyrbek Ktaybekov, Muxammed Mamutov & Ulbosin Saparova. Wind potential and prospects for the construction of wind power plants in the Republic of Karakalpakstan // *AIP Conf. Proc.* 3331, 070001 (2025) <https://doi.org/10.1063/5.0306637>
43. Kadiyala, A., Kommalapati, R., Huque, Z. Quantification of the Lifecycle Greenhouse Gas Emissions from Nuclear Power Generation Systems // *Energies*, 2016, Vol. 9, No. 11, P. 863. <https://doi:10.3390/en9110863>
44. Khanam, T., Kiggundu-Musoke, M.G., Madaminov, M. [et al.]. Renewable energy in Central Asia: An overview of potential, deployment, outlook, and barriers // *Energy Reports*. 2021. Vol. 7. P. 3125–3136. <https://DOI:10.1016/j.egyr.2021.05.040>
45. Nicholson, S. Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update / S. Nicholson, G. Heath. Golden, CO: National Renewable Energy Laboratory, 2021. NREL/FS-6A50-80580. URL: <https://www.nrel.gov/docs/fy21osti/80580.pdf>
46. Huijbregts MAJ, et al. ReCiPe 2016: A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. Report I: Characterization. National Institute for Public Health and the Environment (RIVM), 2016. <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf>
47. Treyer, K., Bauer, C. Life cycle inventories of electricity generation and power supply in version 3 of the Ecoinvent database – part I: electricity generation // *International Journal of Life Cycle Assessment*, 2013, Vol. 21, P. 1236–1254. <https://doi:10.1007/s11367-013-0665-2>
48. Ecoinvent: Overview and Methodology – Data Quality Guidelines. Available at: [https://lca-net.com/files/Overview\\_and\\_methodology.pdf](https://lca-net.com/files/Overview_and_methodology.pdf)
49. IEA-PVPS. Environmental Life Cycle Assessment of Electricity from PV Systems. Fact Sheet 2021–2022. <https://iea-pvps.org/fact-sheets/factsheet-environmental-life-cycle-assessment-of-electricity-from-pv-systems>
50. Allaev K.R. (2007). *Energy of the world and Uzbekistan*. 384 p.
51. Allaev K.R. (2021). *Modern energy and its development prospects*. 649 p.
52. European Commission, Joint Research Centre. European Platform on Life Cycle Assessment (EPLCA). Brussels: JRC, 2024. <https://eplca.jrc.ec.europa.eu/>
53. Technical University of Denmark. Global Wind Atlas 3.0. Roskilde: DTU Wind Energy, 2023. Available at: <https://globalwindatlas.info>
54. Strantzali, E., Aravossis, K. Decision making in renewable energy investments: A review // *Renewable and Sustainable Energy Reviews*, 2016, Vol. 55, P. 885–898. <https://doi.org/10.1016/j.rser.2015.11.021>.
55. Hwang, C.-L., Yoon, K. *Multiple Attribute Decision Making: Methods and Applications*. Berlin: Springer, 1981.
56. Opricovic, S. *Multicriteria Optimization of Civil Engineering Systems*. Belgrade: Faculty of Civil Engineering, 1998.
57. Wernet, G., Bauer, C., Steubing, B. et al. The Ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21, 1218–1230 (2016). <https://doi.org/10.1007/s11367-016-1087-8>.
58. Thinkstep. GaBi Databases 2019 Edition. Leinfelden-Echterdingen: Thinkstep AG, 2019. <https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/source.xhtml?uuid=cb50c596-16b4-44e4-b1aa-319319a79fb5>
59. GB/T 39793-2021. Life cycle assessment of photovoltaic systems. Beijing: Standardization Administration of China (SAC), 2021. <https://www.nature.com/research-intelligence/nri-topic-summaries/life-cycle-assessment-of-photovoltaic-systems-micro-50989>
60. Cherubini, F. et al. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations // *Resources, Conservation and Recycling*, 2009, Vol. 53, P. 434–447. <https://doi.org/10.1016/j.resconrec.2009.03.013>
61. Muench, S., Guenther, E. A systematic review of bioenergy life cycle assessments // *Applied Energy*, 2013, Vol. 112, P. 257–273. <https://doi.org/10.1016/j.apenergy.2013.06.001>.
62. Peters, J.F. et al. The environmental impact of Li-Ion batteries and the role of key parameters – A review // *Renewable and Sustainable Energy Reviews*, 2017, Vol. 67, P. 491–506. <https://doi.org/10.1016/j.rser.2016.08.039>.