

DECISION FRAMEWORK FOR ASSESSING THE ENVIRONMENTAL SAFETY OF RENEWABLE ENERGY IN AGRI-FOOD SYSTEMS

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INTRODUCTION

Climate change, resource degradation and the commitment to climate neutrality have turned the energy base of agricultural production into a structural problem rather than a technical one. Global renewable capacity passed 3,870 GW in 2023, after a record annual addition of 473 GW¹. The Net Zero by 2050 scenario of the International Energy Agency requires that pace to triple, to roughly 1,100 GW a year by 2030². Agri-food systems sit at the centre of this trajectory: they are at once a major energy consumer, a significant source of greenhouse gas emissions, and an important arena for renewable deployment³.

The relationship between renewable energy and agri-food systems is therefore bidirectional, and more intricate than a simple substitution of fossil fuels. Agrivoltaics, biogas from agricultural residues, small wind installations on farmland and distributed rooftop photovoltaics form a technology set with an environmental signature of its own – and with methodological problems to match. Impact allocation between the agricultural and the energy function remains unresolved in Agri-PV; the global warming potential (GWP) of bioenergy swings with the accounting convention adopted for avoided methane; and large-scale infrastructure raises the risk of landscape fragmentation⁴.

¹ International Renewable Energy Agency. Renewable capacity statistics 2024. Abu Dhabi : IRENA, 2024. URL: <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>

² International Energy Agency. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. 2023 Update. Paris : IEA, 2023. URL: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>

³ Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / ed. by P. R. Shukla et al. Cambridge ; New York : Cambridge University Press, 2022. DOI: 10.1017/9781009157926

⁴ Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / ed. by P. R. Shukla et al. Cambridge ; New York : Cambridge University Press, 2022. DOI: 10.1017/9781009157926 ; Chatzipanagi A., Taylor N., Jaeger-Waldau A. Overview of the potential and challenges for agri-photovoltaics in the European Union. Luxembourg : Publications Office of the European Union, 2023. EUR 31482 EN. DOI: 10.2760/208702

The state of the art addresses these problems through three method families grown in largely separate traditions. Life Cycle Assessment (LCA) quantifies environmental burdens across the full life cycle; multi-criteria decision-making (MCDM) ranks competing alternatives under heterogeneous criteria; system dynamics (SD) models long-term feedback behaviour. Reviews of energy planning confirm that all three are applied to renewable systems⁵. What the literature withholds is an account of when each should be used: comparative studies describe the methods but rarely formalise the choice between them.

The unresolved question is not whether LCA, MCDM or SD is superior, but under which combinations of data quality, analytical purpose and regulatory context each becomes defensible, and how conflicting signals should be resolved. Without explicit criteria, method choice may follow disciplinary habit or software availability, reducing comparability. This problem is acute in transition economies, where incomplete verified and representative LCI coverage limits the transferability of Western European models. In Ukraine, EU integration requires methodological alignment, while the armed conflict has disrupted statistical continuity and primary data collection.

This chapter proposes a decision framework for choosing among LCA, MCDM and SD when the environmental safety of renewable energy projects in agri-food systems is at issue. Two questions guide it: how does the choice of methodological framework shape assessment outcomes for such projects in transition economies, and how can that choice be made explicit and auditable?

The chapter therefore develops a three-parameter selection procedure that distinguishes attributional from consequential LCA and derives hybridisation from diagnosed data, purpose and regulatory conditions.

1. Conceptual and Methodological Foundations

Scope and technological categories. This study takes green energy narrowly: electricity and heat generated from renewable sources whose life cycle greenhouse gas emissions are substantially lower than those of fossil alternatives. Nuclear power falls outside the scope, since its assessment belongs to a separate discourse on long-lived waste and low-probability, high-consequence risk that would blur the selection problem at issue here. Within agri-food systems, green energy spans five categories: ground-mounted agrivoltaics (Agri-PV); biogas from agricultural residues; small wind installations on farmland; distributed

⁵ Pohekar S. D., Ramachandran M. Application of multi-criteria decision making to sustainable energy planning : a review. *Renewable and Sustainable Energy Reviews*. 2004. Vol. 8. № 4. P. 365–381. DOI: 10.1016/j.rser.2003.12.007 ; Strantzali E., Aravossis K. Decision making in renewable energy investments : a review. *Renewable and Sustainable Energy Reviews*. 2016. Vol. 55. P. 885–898. DOI: 10.1016/j.rser.2015.11.021

rooftop photovoltaics; and solid biomass from dedicated energy crops. Each engages agroecosystems through a different mechanism, and that mechanism conditions which assessment method fits.

The dual function of the agricultural landscape. Renewable energy in agri-food systems turns on a single conceptual feature: the agricultural landscape does two jobs at once, the same hectare serving as a productive resource for food and as a physical carrier for energy infrastructure. In Agri-PV this duality creates an allocation problem that the ISO 14040/14044 framework does not settle by prescribed rule. No standardised convention divides the environmental burden of the installation between the crop and the kilowatt-hour, and different allocation choices yield materially different GWP values for one and the same physical system.

In bioenergy the duality runs along the chain agricultural residues → biogas + digestate → electricity + organic fertiliser, where the choice of system boundary changes the result outright. Digestate treated as a co-product carrying its own burden share, as an avoided-burden credit against mineral fertiliser, or as a waste stream yields three different verdicts on one plant; comparable sensitivity is documented across bioenergy systems, where energy-based, economic and system-expansion allocation diverge significantly in GWP and other impact categories⁶. The same chain shows why the discussion cannot remain within a purely energetic frame. Converting residues into energy and a nutrient-bearing soil amendment is a waste valorisation pathway that closes a nutrient loop at farm or community scale – in circular economy terms, industrial symbiosis between agricultural production and energy generation. Methods that register only the energy output will misrepresent such systems systematically.

Environmental safety as an umbrella construct. *Environmental safety* is polysemic: depending on disciplinary tradition it denotes the absence of threats to human health, the preservation of ecosystem functionality, or compliance with regulatory limits, and in the international LCA literature the neighbouring notions – environmental performance, environmental impacts, environmental risk – are none of them exact synonyms. The term is retained here as an author-defined umbrella construct whose content is fixed explicitly rather than assumed, namely a multidimensional construct of four dimensions:

- 1) climatic – global warming potential over a 100-year horizon, expressed in g CO₂-eq. kWh⁻¹;
- 2) ecosystem – eutrophication, acidification, land use and freshwater ecotoxicity;

⁶ Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review / A. I. Osman [et al.]. *Environmental Chemistry Letters*. 2024. Vol. 22, no. 3. P. 1115–1154. DOI: 10.1007/s10311-023-01694-z.

- 3) resource – abiotic resource depletion and freshwater consumption;
- 4) toxicological – human toxicity.

These are conceptual categories, not the impact categories of any single characterisation method. They are operationalised at the goal and scope stage by selecting the corresponding indicators from a clearly identified and established life cycle impact assessment (LCIA) method⁷. Because impact-category definitions and indicators vary across LCIA methods, every application must name the method used and the indicator representing each dimension. Mixing terminology drawn from different methods within one indicator set is a reporting error, not a stylistic choice.

Expressing the construct through life cycle indicators secures comparability across dimensions and guards against the *single-target trap*, in which optimising one indicator conceals deterioration in another: attention confined to GWP can mask rising eutrophication from digestate application, or soil degradation under monocultural energy cropping. The hazard is acute in agri-food systems, where soil and water are at once the object of protection and the productive base; the diagnostic limits of single-indicator screening are well established⁸. Because the four dimensions differ in measurability, time constant and policy relevance, no one method captures them all. LCA locates life cycle hotspots and supports targeted mitigation within a systemic view of agroecosystems⁹, yet it neither weighs social acceptability nor models feedback over decades. The case for comparative systematisation follows from the construct itself.

Positioning the technological approach. Earlier work systematised approaches to sustainable resource use in agri-food systems along five directions¹⁰. This chapter develops the innovation-technological direction through a comparative typology of the three assessment methods (Table 1).

⁷ Guinée J. B. (ed.). Handbook on life cycle assessment : operational guide to the ISO standards. Dordrecht : Kluwer Academic Publishers, 2002. DOI: 10.1007/0-306-48055-7

⁸ Laurent A., Olsen S. I., Hauschild M. Z. Limitations of carbon footprint as indicator for environmental sustainability and LCA-based screening tools. *Environmental Science & Technology*. 2012. Vol. 46. № 8. P. 4100–4108. DOI: 10.1021/es204163f

⁹ Lulovicova A., Bouissou S. Life cycle assessment as a prospective tool for sustainable agriculture and food planning at a local level. *Geography and Sustainability*. 2024. Vol. 5. № 2. P. 251–264. DOI: 10.1016/j.geosus.2024.01.008

¹⁰ Пузік В. К., Криштон Є. А. Системний підхід до екологічно збалансованого природокористування: концептуальні моделі, аналітичні рамки та індикатори. *Методологічні підходи та практичне обґрунтування екологічно збалансованого природокористування і шляхи зниження антропогенного навантаження на природні і штучні екосистеми у сфері АПК* : звіт про НДР (остаточний) / Державний біотехнологічний університет. Харків, 2025. Розд. VII. С. 213–244. № держреєстрації 0121U107701. URL: <https://repo.btu.kharkiv.ua/server/api/core/bitstreams/4d9ea1b4-3100-42e0-80f8-f53ff23f8ed5/content>

Table 1

Conceptual typology of methodological approaches to assessing sustainable resource use in agri-food systems

<i>Criterion</i>	<i>Systems approach (DPSIR / SES)</i>	<i>Ecosystem approach</i>	<i>Landscape-ecological approach</i>	<i>Technological approach (LCA / MCDM / SD)</i>
Object of analysis	The agricultural system as a socio-ecological-technical system; actors, resources, rules	Ecosystem functionality; services and their interlinkages	Spatial organisation of agricultural landscapes; fragmentation, connectivity	Product, technology or project; material and energy flows
Analytical framework	DPSIR; SES framework (Ostrom); planetary boundaries	CBD, IPBES, TEEB; ecosystem services concept	Landscape metrics (FRAGSTATS); GIS analysis	LCA (ISO 14040/14044); MCDM (AHP, TOPSIS); system dynamics
Spatial scale	Field or farm to macro-policy	Plot to catchment	Landscape or region; agroclimatic zone	Product to system; cradle-to-grave or cradle-to-gate
Time horizon	Medium to long term; iterative	Long term (succession, climatic cycles)	Medium term (10–50 years)	SD: 15–50 years; LCA: static; MCDM: present state
Principal strength	Comprehensive representation of cause–effect relations	Attention to systemic integrity and services	Spatial diagnosis of degradation and restoration	Quantitative impact assessment; comparison of alternatives
Principal limitation	Difficulty of collecting multidimensional data	Non-standardised valuation of services	Dependence on detailed GIS data	Scarcity of local inventories in transition economies

Source: developed by the author on the basis of¹¹.

¹¹ Strantzali E., Aravossis K. Decision making in renewable energy investments : a review. *Renewable and Sustainable Energy Reviews*. 2016. Vol. 55. P. 885–898. DOI: 10.1016/j.rser.2015.11.021 ; Guinée J. B. (ed.). *Handbook on life cycle assessment : operational guide to the ISO standards*. Dordrecht : Kluwer Academic Publishers, 2002. DOI: 10.1007/0-306-48055-7 ; Пузік В. К., Криштоп Є. А. Системний підхід до екологічно збалансованого природокористування: концептуальні моделі, аналітичні рамки та індикатори. *Методологічні підходи та практичне обґрунтування екологічно збалансованого природокористування і шляхи зниження антропогенного навантаження на природні і штучні екосистеми у сфері АПК* : звіт про НДР (остаточний) / Державний біотехнологічний університет. Харків, 2025. Розд. VII. С. 213–244. № держреєстрації 0121U107701. URL: <https://repo.btu.kharkiv.ua/server/api/core/bitstreams/4d9ea1b4-3100-42e0-80f8-f53ff23f8ed5/content> ; Forrester J. W. *Industrial dynamics*. Cambridge, MA : MIT Press, 1961.

Table 1 shows the technological approach complementing rather than displacing the systems and landscape-ecological traditions: DPSIR and the SES framework supply the criteria structure and the governance context, while LCA, MCDM and SD deliver quantitative assessment of specific options.

Ecosystem interactions of green energy technologies. The complementarity of methodological approaches must be considered in relation to the ecological processes that actually unfold in agroecosystems. Empirical evidence shows that ground-mounted photovoltaic systems alter local air and soil microclimates, soil moisture, vegetation biomass and plant-species diversity, with effects varying across seasons and management regimes¹². Habitat-enhancing agrivoltaic configurations may improve pollinator supply, water retention, sediment retention and carbon storage relative to conventional agricultural practice, although these findings are model-based and require field validation¹³.

More broadly, territorial LCA can support environmental planning in local agri-food systems by identifying environmental impacts and trade-offs across alternative scenarios¹⁴. Taken together, these studies indicate that environmental outcomes are context- and management-dependent: appropriate management can enhance ecosystem functions, whereas poorly adapted siting and management practices may create localised risks. Table 2 summarises these interactions by technology.

Table 2

**Ecological interactions of green energy technologies
in agricultural landscapes**

<i>Renewable technology</i>	<i>Soil resources</i>	<i>Water resources</i>	<i>Biodiversity</i>	<i>Landscape structure</i>
Agri-PV (ground-mounted)	Panel shading alters soil temperature and moisture; summer cooling and local drying have been observed beneath PV arrays ¹ .	Water-retention effects depend on system configuration and vegetation management; habitat-enhancing scenarios have shown modelled gains in water retention ² .	Plant biomass and species diversity may decline beneath conventional PV arrays ³ , whereas habitat-enhancing agrivoltaic configurations may increase pollinator supply ⁴ .	Altered visual structure; requires GIS-based connectivity assessment

¹² Armstrong A., Ostle N. J., Whitaker J. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*. 2016. Vol. 11. № 7. Article 074016. DOI: 10.1088/1748-9326/11/7/074016

¹³ Enhancing ecosystem services and biodiversity in agrivoltaics through habitat-enhancing strategies / A. Ludzuweit et al. *Renewable and Sustainable Energy Reviews*. 2025. Vol. 212. Article 115380. DOI: 10.1016/j.rser.2025.115380

¹⁴ Lulovicova A., Bouissou S. Life cycle assessment as a prospective tool for sustainable agriculture and food planning at a local level. *Geography and Sustainability*. 2024. Vol. 5. № 2. P. 251–264. DOI: 10.1016/j.geosus.2024.01.008

Table 2 (Continued)

<i>Renewable technology</i>	<i>Soil resources</i>	<i>Water resources</i>	<i>Biodiversity</i>	<i>Landscape structure</i>
Biogas from agricultural residues	Digestate can affect soil organic matter and improve selected soil physical properties, although outcomes are site- and management-dependent ⁵ .	Nitrate-leaching risk depends on digestate characteristics, soil type, application rate and the synchrony of nitrogen supply with crop demand; timely nutrient characterisation and crop-matched application reduce over-fertilisation risk ⁶ .	Context-dependent effects on soil biota: possible short-term earthworm mortality or avoidance, but neutral or positive longer-term responses ⁷ .	Localised landscape effects associated with digesters and storage facilities
Wind installations on farmland	Minimal permanent land withdrawal, although construction and access roads may cause local soil disturbance and compaction.	No substantial direct effect on the water regime under normal operation; local construction-related effects remain site-specific.	Site- and species-specific collision, disturbance, displacement and barrier risks for birds and bats; reduced through ecological screening, avoidance of sensitive habitats and major flyways, appropriate turbine siting and, where necessary, operational curtailment ⁸ .	Altered landscape silhouette; spatial suitability and social acceptability require site-specific assessment.
Distributed rooftop PV	No direct effect; no agricultural land occupation	No direct interaction with agricultural water resources during normal operation	Limited direct effect; no additional land occupation	Minimal landscape effect; potential building-level visual considerations
Energy crops (miscanthus, willow)	Perennial Miscanthus and willow can increase soil organic carbon when replacing annual arable crops, although outcomes depend on previous land use, soil conditions and plantation age ⁹ .	Water use may exceed that of annual arable crops, particularly for willow short-rotation coppice; effects on evapotranspiration and local water balance are site-specific and depend on precipitation, soil conditions, groundwater availability, crop species and stand age ¹⁰ .	Relative to intensive arable cropping, Miscanthus and willow can provide additional habitat and support greater biodiversity, although outcomes depend on crop structure, management, plantation age and the surrounding landscape ¹¹ .	Plantation size and spatial configuration alter landscape structure; appropriately located perennial energy crops can increase heterogeneity in intensively arable landscapes, although effects vary by crop and spatial scale ¹² .

Source: developed by the author from the sources cited in the table.

Three regularities emerge. Agri-PV and bioenergy require assessment beyond the climatic dimension; rooftop PV has comparatively limited direct interaction with agroecosystems; and no technology is preferable independently

of context. The framework must therefore represent both local ecological risks and circular-economy benefits, including nutrient-loop closure, residue valorisation and avoided agricultural land occupation.

Figure 1 shows renewable technologies generating distinct yet overlapping challenges. Agrivoltaics and residue-based biogas are associated primarily with impact allocation, while biogas additionally exhibits substantial GWP variability arising from system-boundary choices, methane-accounting conventions and LCA orientation; wind installations and dedicated energy crops raise landscape and spatial concerns, and energy crops introduce a direct food-energy trade-off. Limited coverage of verified, representative Ukrainian LCI data acts as a cross-cutting constraint under transition-economy conditions. The terminal node, “Need for structured method selection”, expresses the requirement to reconcile technology-specific challenges with data conditions and assessment requirements; the corresponding framework is developed in Section 3.

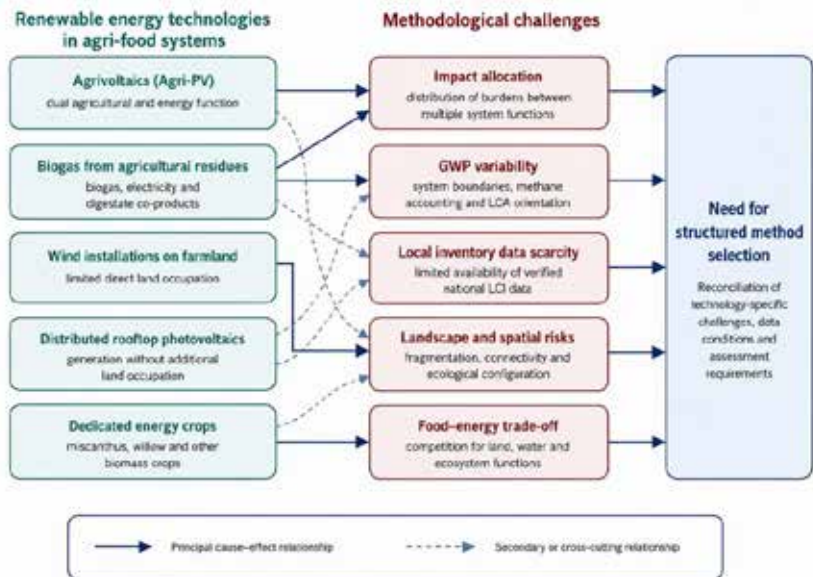


Fig. 1. Problem architecture linking renewable energy technologies in agri-food systems to technology-specific methodological challenges and the resulting need for explicit method selection. Solid arrows indicate principal cause-effect relationships; dashed arrows indicate secondary or cross-cutting relationships

Source: developed by the author from the literature synthesis presented in Section 1 and Table 2.

The regulatory determinants of method choice. Analytical considerations do not govern method selection alone. Three regulatory frameworks bear on Ukraine. The United Nations Sustainable Development Goals, SDG 7 and SDG 13 in particular, set the normative baseline. The European Green Deal, with the Fit for 55 package and the Farm to Fork and Bioeconomy strategies, supplies the operative instruments: the EU Taxonomy requires demonstration of substantial contribution and compliance with the do no significant harm (DNSH) principle across six environmental objectives, its technical screening criteria set activity by activity and its evidence requirements varying accordingly¹⁵; the Environmental Footprint methods furnish a standardised life-cycle basis for environmental claims, grounded in attributional LCA¹⁶; and the Corporate Sustainability Reporting Directive obliges large undertakings to disclose taxonomy-aligned data. The EU – Ukraine Association Agreement and candidate status granted in 2022 turn methodological harmonisation from an option into a policy requirement.

Life cycle thinking is thus entering decision processes through these methods¹⁷, while global decarbonisation strategies press for integrated systems analysis¹⁸. Method selection must therefore satisfy scientific and regulatory criteria at once – a demand that Section 2 tests against the three candidate methods.

2. Comparative Analysis of Assessment Methods

Review protocol. The targeted methodological review was reported using the applicable items and flow diagram of the PRISMA 2020 statement¹⁹, which updates the 2009 statement²⁰ and supports transparent reporting of record

¹⁵ Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 by establishing technical screening criteria. *Official Journal of the European Union*. 2021. L 442. P. 1–349. URL: https://eur-lex.europa.eu/eli/reg_del/2021/2139/oj

¹⁶ Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*. 2021. L 471. P. 1–396. URL: <https://eur-lex.europa.eu/eli/reco/2021/2279/oj>; European Commission, Joint Research Centre. Environmental Footprint methods. URL: <https://epfca.jrc.ec.europa.eu/EnvironmentalFootprint.html>

¹⁷ Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*. 2021. L 471. P. 1–396. URL: <https://eur-lex.europa.eu/eli/reco/2021/2279/oj>; European Commission, Joint Research Centre. Environmental Footprint methods. URL: <https://epfca.jrc.ec.europa.eu/EnvironmentalFootprint.html>

¹⁸ International Energy Agency. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. 2023 Update. Paris : IEA, 2023. URL: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>

¹⁹ The PRISMA 2020 statement: an updated guideline for reporting systematic reviews / M. J. Page et al. *BMJ*. 2021. Vol. 372. Article n71. DOI: 10.1136/bmj.n71

²⁰ Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement / D. Moher et al. *PLoS Medicine*. 2009. Vol. 6. № 7. Article e1000097. DOI: 10.1371/journal.pmed.1000097

identification, screening and inclusion. PRISMA was used as a reporting framework rather than as a claim that the review constituted an exhaustive global systematic review. The review sought to characterise approaches retrieved through the predefined targeted strategy, identify methodological imbalances within that sample, and establish the case for integration. The review protocol was not prospectively registered.

The searches were run in Scopus and the Web of Science Core Collection on 15 January 2026. Filters were applied for document type (article, review) and subject area (environmental science, energy, agriculture); the publication window ran from 2019 to 2024, and languages were English and Ukrainian. One conceptual strategy was executed in both databases, the field tag adapted to each: TITLE-ABS-KEY in Scopus, Topic (TS) in Web of Science. An outer bracket encloses the three method blocks, so that every retrieved record satisfies the method condition together with each of the four conditions that follow:

((“life cycle assessment” OR LCA OR “attributional LCA” OR “consequential LCA”) OR (“multi-criteria decision making” OR MCDM OR AHP OR TOPSIS OR VIKOR) OR (“system dynamics”)) AND (“renewable energy” OR RES OR bioenergy OR biogas OR agrivoltaic* OR “agri-PV” OR wind OR photovoltaic*) AND (“environmental safety” OR “environmental impact” OR sustainability) AND (agricultur* OR “agro-industrial complex” OR agri-food OR agroecosystem*) AND (“transition econom*” OR Ukraine OR “Eastern Europe”)

Deduplication ran in two passes: records were matched automatically on DOI, and those lacking a DOI or registered divergently were then matched manually on title, first author and publication year, the journal version being retained wherever a study appeared as both preprint and article. The geographical component was included deliberately to retrieve studies potentially relevant to transition-economy, Ukrainian or Eastern European contexts. The occurrence of one or more of these terms in the searchable bibliographic fields was a retrieval condition but did not necessarily mean that a study was empirically focused on a transition economy; geographical focus was subsequently coded from the empirical study area rather than from the matched search term. The review is therefore a targeted methodological review rather than a statistically representative mapping of the global literature: its aim was not to quantify worldwide publication patterns but to identify approaches potentially applicable under transition-economy conditions. Accordingly, the frequencies reported below characterise the targeted analytical sample rather than the global research field.

The PRISMA analytical sample and the supplementary evidence base were kept separate. All quantitative analyses used only the 87 eligible peer-reviewed studies published within the predefined 2019–2024 window. Publications

from 2025 identified during post-review verification, including²¹, as well as institutional reports, foundational or other out-of-window publications, and technology-specific sources²², were used only for contextual interpretation and did not enter the PRISMA counts, cluster frequencies or identification of the research gap. Consequently, the analytical sample does not capture the complete 2025 literature and may underrepresent the most recent methodological developments. Sources²³ remained outside the analytical sample because they

²¹ Enhancing ecosystem services and biodiversity in agrivoltaics through habitat-enhancing strategies / A. Ludzuweit et al. *Renewable and Sustainable Energy Reviews*. 2025. Vol. 212. Article 115380. DOI: 10.1016/j.rser.2025.115380 ; Tighnavard Balasbanch A., Aldrovandi S., Sher W. A systematic review of implementing multi-criteria decision-making (MCDM) approaches for the circular economy and cost assessment. *Sustainability*. 2025. Vol. 17. № 11. Article 5007. DOI: 10.3390/su17115007 ; Mlybari E. A. Smart sustainability in construction: an integrated LCA–MCDM framework for climate-adaptive material selection in educational buildings. *Sustainability*. 2025. Vol. 17. № 21. Article 9650. DOI: 10.3390/su17219650 ; A critical review of life cycle assessment of renewable agricultural systems / M. Kiehbadrounizhad et al. *Sustainable Energy Technologies and Assessments*. 2025. Vol. 73. Article 104100. DOI: 10.1016/j.seta.2024.104100

²² Long-term application of biogas digestate improves soil physical properties / M. Mayerová et al. *Soil and Tillage Research*. 2023. Vol. 231. Article 105715. DOI: 10.1016/j.still.2023.105715 ; Recycling of biogas digestates in plant production: NPK fertilizer value and risk of leaching / T. A. Sogn et al. *International Journal of Recycling of Organic Waste in Agriculture*. 2018. Vol. 7. P. 49–58. DOI: 10.1007/s40093-017-0188-0 ; Digestate in replacement of synthetic fertilisers: a comparative 3-year field study of the crop performance and soil residual nitrates in West-Flanders / G. Reuland et al. *European Journal of Agronomy*. 2024. Vol. 161. Article 127380. DOI: 10.1016/j.eja.2024.127380 ; Short- and long-term impacts of anaerobic digestate spreading on earthworms in cropped soils / V. Moinard et al. *Applied Soil Ecology*. 2021. Vol. 168. Article 104149. DOI: 10.1016/j.apsoil.2021.104149 ; European Commission. Directorate-General for Environment. Guidance document on wind energy developments and EU nature legislation. Luxembourg : Publications Office of the European Union, 2020. DOI: 10.2779/095188 ; Harris Z. M., Spake R., Taylor G. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy*. 2015. Vol. 82. P. 27–39. DOI: 10.1016/j.biombioe.2015.05.008 ; A review of the impacts of Short Rotation Coppice cultivation on water issues / I. Dimitriou et al. *Landbauforschung*. 2009. Vol. 59. № 3. P. 197–206 ; Dedicated biomass crops can enhance biodiversity in the arable landscape / A. J. Haughton et al. *GCB Bioenergy*. 2016. Vol. 8. № 6. P. 1071–1081. DOI: 10.1111/gcbb.12312 ; Landscape metrics and land-use patterns of energy crops in the agricultural landscape / X. Xu et al. *BioEnergy Research*. 2023. Vol. 16. P. 2178–2191. DOI: 10.1007/s12155-023-10584-9

²³ Long-term application of biogas digestate improves soil physical properties / M. Mayerová et al. *Soil and Tillage Research*. 2023. Vol. 231. Article 105715. DOI: 10.1016/j.still.2023.105715 ; Recycling of biogas digestates in plant production: NPK fertilizer value and risk of leaching / T. A. Sogn et al. *International Journal of Recycling of Organic Waste in Agriculture*. 2018. Vol. 7. P. 49–58. DOI: 10.1007/s40093-017-0188-0 ; Digestate in replacement of synthetic fertilisers: a comparative 3-year field study of the crop performance and soil residual nitrates in West-Flanders / G. Reuland et al. *European Journal of Agronomy*. 2024. Vol. 161. Article 127380. DOI: 10.1016/j.eja.2024.127380 ; Short- and long-term impacts of anaerobic digestate spreading on earthworms in cropped soils / V. Moinard et al. *Applied Soil Ecology*. 2021. Vol. 168. Article 104149. DOI: 10.1016/j.apsoil.2021.104149 ; European Commission. Directorate-General for Environment. Guidance document on wind energy developments and EU nature legislation. Luxembourg : Publications Office of the European Union, 2020. DOI: 10.2779/095188 ; Harris Z. M., Spake R., Taylor G. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy*. 2015. Vol. 82. P. 27–39. DOI: 10.1016/j.biombioe.2015.05.008 ; A review of the impacts of Short Rotation Coppice cultivation on water issues / I. Dimitriou et al. *Landbauforschung*. 2009. Vol. 59. № 3. P. 197–206 ; Dedicated biomass crops can enhance biodiversity in the arable landscape / A. J. Haughton et al. *GCB Bioenergy*. 2016. Vol. 8. № 6. P. 1071–1081. DOI: 10.1111/gcbb.12312 ; Landscape metrics and land-use patterns of energy crops in the agricultural landscape / X. Xu et al. *BioEnergy Research*. 2023. Vol. 16. P. 2178–2191. DOI: 10.1007/s12155-023-10584-9

fell outside the publication window or did not use LCA, MCDM or SD as the principal analytical instrument.

Selection process and sample. The search identified 512 records across the two databases. Duplicate removal ($n = 170$) left 342 unique records for title and abstract screening, from which 164 full-text reports were assessed for eligibility and 87 peer-reviewed articles and reviews entered the final analytical sample (Figure 2).

A single reviewer conducted the screening and reassessed borderline cases through repeated full-text examination against the predefined criteria; no independent second reviewer took part – a limitation of the review, revisited among the validity considerations below. Title-and-abstract screening excluded 178 records on thematic or language grounds, leaving 164 reports to be retrieved. Full-text assessment then excluded 77 on three grounds: no explicit methodological approach ($n = 32$); a technical focus without substantive environmental analysis ($n = 21$); and no relevance to agri-food systems ($n = 24$).

Inclusion required relevance to renewable energy assessment in agri-food systems; LCA, MCDM or SD as the principal analytical instrument rather than a descriptive element; an environmental or systems perspective; peer-reviewed article or review status; an available full text; and publication within 2019–2024. Records failing any of these conditions, or duplicating another record, were excluded.

Data extraction and synthesis. Data were extracted from each included study on a structured coding form built for this review. The variables were publication year, geographical focus, renewable energy technology, principal methodological approach, LCA orientation and MCDM technique where applicable, analytical scale, temporal perspective, data characteristics, and reported treatment of uncertainty. Every study was assigned to one of three mutually exclusive principal methodological clusters: LCA, MCDM, or system dynamics and integrated approaches. Secondary methodological components were coded separately. Technologies were classified by the primary technology investigated, and geographical context was coded from the empirical study area rather than from author affiliation. Descriptive frequencies and proportions were calculated only for the mutually exclusive principal methodological and renewable-energy technology classifications. The remaining variables informed qualitative methodological comparison and were not summarised as frequencies because they were conditional, non-mutually exclusive or incompletely reported across studies. Reported treatment of uncertainty informed the qualitative discussion of limitations rather than a separate frequency estimate. No formal risk-of-bias assessment or quality scoring was undertaken, since the purpose

was methodological mapping rather than quantitative evidence synthesis. The structured coding form and the study-level list of the 87 included publications are retained in the author’s working materials and are available from the author upon request.

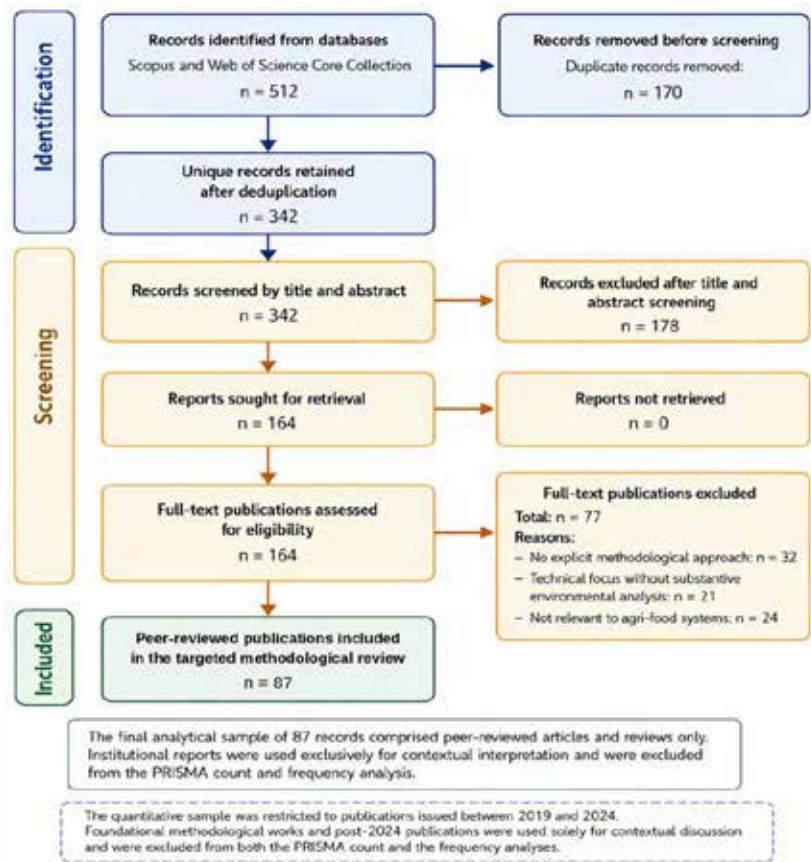


Fig. 2. PRISMA 2020 flow diagram documenting record identification, deduplication, title-and-abstract screening, report retrieval, full-text eligibility assessment and formation of the final analytical sample of 87 peer-reviewed articles and reviews

Source: developed by the author in accordance with the PRISMA 2020 statement²⁴

²⁴ The PRISMA 2020 statement: an updated guideline for reporting systematic reviews / M. J. Page et al. *BMJ*. 2021. Vol. 372. Article n71. DOI: 10.1136/bmj.n71

Structure of the targeted analytical sample. Analysis of the final sample (n = 87) identified three mutually exclusive principal methodological clusters:

- LCA – n = 32 (36.8%);
- MCDM – n = 30 (34.5%);
- system dynamics and integrated approaches – n = 25 (28.7%).

Across the full analytical sample, the dominant renewable-energy technologies were photovoltaics – n = 37 (42.5%), wind energy – n = 27 (31.0%), bioenergy – n = 16 (18.4%), and other or mixed technologies – n = 7 (8.0%).

Cluster and technology percentages use n = 87 and mutually exclusive study classifications. MCDM technique was coded as a conditional, non-mutually exclusive attribute and was used only for qualitative methodological comparison.

Studies focused on EU Member States and the United Kingdom predominated within the targeted sample, whereas only 10 studies (11.5%) explicitly addressed transition-economy contexts. Despite the inclusion of transition-economy terminology in the search strategy, few studies offered empirical analysis directly applicable to such settings. Within this targeted sample, the distribution indicates a continuing shortage of methodological work on environmental assessment under transition-economy conditions, limiting the transferability of existing approaches to Ukraine and supporting the need for context-specific development. Related reviews identify methodological and implementation constraints in sustainable construction in developing countries²⁵ and in the application of MCDM to circular-economy and cost-assessment problems²⁶. These studies provide relevant contextual evidence of broader implementation challenges, but neither directly documents the availability or representativeness of Ukrainian LCI data.

Recent research reports growing integration of LCA and MCDM in sustainability assessment, including renewable-energy and waste-management applications²⁷. These studies, however, do not provide an explicit rule for

²⁵ Establishing the limitations of sustainable construction in developing countries: a systematic literature review using PRISMA / O. E. Ogunmakinde et al. *Smart and Sustainable Built Environment*. 2024. Vol. 13. № 3. P. 609–624. DOI: 10.1108/SASBE-10-2022-0223

²⁶ Tighnavard Balasbانه A., Aldrovandi S., Sher W. A systematic review of implementing multi-criteria decision-making (MCDM) approaches for the circular economy and cost assessment. *Sustainability*. 2025. Vol. 17. № 11. Article 5007. DOI: 10.3390/su17115007

²⁷ A critical review of life cycle assessment of renewable agricultural systems / M. Kiehadrouinezhad et al. *Sustainable Energy Technologies and Assessments*. 2025. Vol. 73. Article 104100. DOI: 10.1016/j.seta.2024.104100 ; Integrating life cycle assessment and multi criteria decision making for sustainable waste management: key issues and recommendations for future studies / A. E. Torkayesh et al. *Renewable and Sustainable Energy Reviews*. 2022. Vol. 168. Article 112819. DOI: 10.1016/j.rser.2022.112819

deciding when integration is warranted. Integration is treated as a design assumption rather than the outcome of a diagnostic step, so hybrids may be adopted where one method would suffice, or a single method may be retained where the data cannot support it. Universal integrated models also remain narrow in scope and require adaptation²⁸.

Existing frameworks also remain calibrated on a data environment that transition economies do not share. The integrated LCA – MCDM designs in the sample presuppose an inventory complete enough to run the LCA component at full resolution; where that presupposition fails, they offer no fallback and no procedure for documenting the resulting bias. That is the Ukrainian situation, and it is why importing an existing hybrid design solves nothing.

Three findings summarise the review. First, life-cycle greenhouse gas emissions from renewable electricity technologies are substantially lower than those from unabated coal generation: IPCC AR5 reports median values of approximately 41–48 g CO₂-eq. kWh⁻¹ for solar photovoltaics and 11–12 g CO₂-eq. kWh⁻¹ for wind, compared with 820 g CO₂-eq. kWh⁻¹ for pulverised coal²⁹. Second, LCA results vary considerably with system boundaries and with attributional or consequential orientation – a material methodological risk that demands explicit documentation³⁰. Third, and decisively for this chapter, no explicitly validated method-selection framework meeting all predefined criteria was identified within the reviewed sample for renewable energy in the agri-food systems of transition economies.

LCA-only studies achieve considerable depth for individual technologies but treat socio-economic and governance factors thinly³¹, whereas integrated approaches acknowledge that no single instrument covers the problem, recent work on renewable integration in agriculture supporting the combination of LCA with multi-criteria methods³². This chapter departs from that literature in one respect: it treats the combination itself as a decision to be justified rather

²⁸ Mlybari E. A. Smart sustainability in construction: an integrated LCA – MCDM framework for climate-adaptive material selection in educational buildings. *Sustainability*. 2025. Vol. 17. № 21. Article 9650. DOI: 10.3390/su17219650

²⁹ Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / ed. by O. Edenhofer et al. Cambridge ; New York : Cambridge University Press, 2014. DOI: 10.1017/CBO9781107415416

³⁰ Laurent A., Olsen S. I., Hauschild M. Z. Limitations of carbon footprint as indicator for environmental sustainability and LCA-based screening tools. *Environmental Science & Technology*. 2012. Vol. 46. № 8. P. 4100–4108. DOI: 10.1021/es204163f

³¹ Dec K. Life cycle assessment of renewable energy sources – key issues. Bibliometric analysis of the literature. *Economics and Environment*. 2024. Vol. 89. № 2. Article 839. DOI: 10.34659/eis.2024.89.2.839

³² A critical review of life cycle assessment of renewable agricultural systems / M. Kiehadrouinezhad et al. *Sustainable Energy Technologies and Assessments*. 2025. Vol. 73. Article 104100. DOI: 10.1016/j.seta.2024.104100

than assumed. Fragmentation is not cured by adding methods, but by specifying the conditions under which each applies.

Life Cycle Assessment. LCA quantifies the environmental burden of products, processes or systems across the full life cycle, either cradle-to-grave or cradle-to-gate. ISO 14040:2006³³ and ISO 14044:2006³⁴ set out its principles, framework and procedural requirements, and the method proceeds in four phases: definition of goal, scope and functional unit; life cycle inventory analysis (LCI); life cycle impact assessment (LCIA); and interpretation. The standards prescribe no fixed list of impact categories; these are selected in accordance with the goal and scope of the study using a documented LCIA method, such as CML-IA³⁵ or the Environmental Footprint methods³⁶. Practice rests on widely used commercial databases such as ecoinvent and Sphera/GaBi, whose geographical coverage remains stronger for Western and Central Europe than for Ukraine.

One decision deserves particular emphasis, because it is so often left implicit. Attributional LCA describes average impacts within a defined technological system and underpins Environmental Product Declarations and the Environmental Footprint methods, which are oriented toward it for regulatory reporting. Consequential LCA models the changes in impacts across a wider system that follow from a decision and may be more appropriate where the assessment question concerns the system-wide consequences of renewable deployment in agri-food systems. Conflating the two is a frequent source of incomparable results.

Established LCA guidance already relates modelling choices to decision context. The ILCD Handbook distinguishes decision situations requiring different modelling approaches, while Ekvall and Weidema formalise consequential system boundaries and data selection³⁷. The contribution of the present framework therefore lies not in introducing the attributional – consequential

³³ ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. Geneva : International Organization for Standardization, 2006.

³⁴ ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. Geneva : International Organization for Standardization, 2006.

³⁵ Guinée J. B. (ed.). Handbook on life cycle assessment: operational guide to the ISO standards. Dordrecht : Kluwer Academic Publishers, 2002. DOI: 10.1007/0-306-48055-7

³⁶ Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*. 2021. L 471. P. 1–396. URL: <https://eur-lex.europa.eu/eli/reco/2021/2279/oj> ; European Commission, Joint Research Centre. Environmental Footprint methods. URL: <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>

³⁷ International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment – Detailed guidance / European Commission, Joint Research Centre, Institute for Environment and Sustainability. First edition. Luxembourg : Publications Office of the European Union, 2010. EUR 24708 EN. DOI: 10.2788/38479 ; Ekvall T., Weidema B. P. System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment*. 2004. Vol. 9. № 3. P. 161–171. DOI: 10.1007/BF02994190

distinction itself, but in embedding it as an explicit choice dimension within a broader selection procedure spanning LCA, MCDM and SD under agri-food and transition-economy constraints.

The principal strength of LCA is standardisation: it offers the firmest life-cycle basis for Environmental Footprint studies and may support compliance assessment under the relevant EU Taxonomy technical screening criteria. The Taxonomy does not, however, prescribe a full LCA for every renewable energy activity – its criteria are activity-specific, and DNSH verification may rest on a range of indicators and documentation. A second strength is that impact coverage extends across several categories, which protects against the single-target trap.

Under transition-economy conditions, the critical limitation is dependence on inventory quality. The coverage of verified, geographically and technologically representative inventories for the Ukrainian processes required in renewable-energy assessment remains insufficient; where proxy datasets are used, they may introduce systematic geographical and technological deviation.

Multi-criteria decision-making. MCDM is a family of methods for structured comparison of alternatives against criteria measured in incommensurable units. For renewable projects in agri-food systems it brings LCA impact indicators, social criteria such as community acceptance and employment, and landscape indicators into a single decision.

The analytic hierarchy process³⁸ builds on pairwise comparisons. The criterion weight w_j is derived as the normalised principal eigenvector of the comparison matrix $\mathbf{A}$, satisfying $\mathbf{A} \cdot \mathbf{w} = \lambda_{max} \cdot \mathbf{w}$ with $\sum w_j = 1$, subject to the consistency condition $CR = CI/RI < 0.10$. TOPSIS³⁹ ranks alternatives by relative distance to the ideal solution: $CC_i = d_i^- / (d_i^+ + d_i^-)$, a higher CC_i marking a preferred alternative.

Sensitivity to weighting is a material risk. Pohekar and Ramachandran⁴⁰ showed that even moderate shifts in weights can reverse a ranking, which makes sensitivity analysis a mandatory component of any MCDM assessment rather than an optional refinement.

For transition economies MCDM offers three advantages: it tolerates imperfect data, accepting partial, ordinal and qualitative indicators; it admits the social and institutional dimension through stakeholder weighting, which matters for renewable decisions in rural communities; and it is compatible

³⁸ Saaty T. L. The analytic hierarchy process: planning, priority setting, resource allocation. New York : McGraw-Hill, 1980.

³⁹ Hwang C.-L., Yoon K. Multiple attribute decision making: methods and applications. Berlin ; Heidelberg : Springer, 1981. DOI: 10.1007/978-3-642-48318-9

⁴⁰ Pohekar S. D., Ramachandran M. Application of multi-criteria decision making to sustainable energy planning : a review. *Renewable and Sustainable Energy Reviews*. 2004. Vol. 8. № 4. P. 365–381. DOI: 10.1016/j.rser.2003.12.007

with the DPSIR framework, where drivers and pressures define the regulatory context, state and impact supply the environmental criteria, and responses represent the management options⁴¹.

System dynamics. Where LCA and MCDM yield static assessments or rankings, SD models complex systems through stocks, flows and feedback loops. Developed by Forrester⁴² and extended by Sterman⁴³, it represents behaviour beyond the reach of the other two. For agri-energy systems it captures three structures: a reinforcing loop reproducing the renewable learning curve, in which rising capacity lowers unit cost, attracts investment and raises capacity further; an illustrative balancing loop in which deteriorating emissions performance triggers policy intervention, investment or substitution responses that may reduce emissions after a delay; and explicit time delays between investment decisions and commissioning.

The principal barrier to SD in Ukraine is the shortage of time series long and internally consistent enough for calibration and validation: since 2022 the armed conflict has disrupted statistical continuity, altered the energy mix and changed production parameters. Models must therefore distinguish wartime from reconstruction regimes explicitly. Over the 2030–2050 horizon, however, SD remains valuable for grounding national renewable energy targets.

Comparative matrix. These differences call for systematic comparison of the domains of applicability and the limits of each approach. Table 3 sets them side by side.

Table 3

Comparative matrix of methodological approaches to assessing the environmental safety of renewable energy in agri-food systems

<i>Criterion</i>	<i>LCA (attributional / consequential)</i>	<i>MCDM (AHP, TOPSIS, VIKOR)</i>	<i>System dynamics (SD)</i>
Input data	Quantitative material and energy inventories; average values for attributional, marginal for consequential	Quantitative and qualitative; tolerates partial or aggregated data; admits expert judgement	Longitudinal data sufficient for calibration and validation; non-linear relations between variables
Scale and horizon	Product, process or project; full life cycle from extraction to disposal	Project, region or strategy; present state or short-term projection	System, region or country; strategic horizon of 15–50 years

⁴¹ Next generation application of DPSIR for sustainable policy implementation / S. A. Carnohan et al. *Current Research in Environmental Sustainability*. 2023. Vol. 5. Article 100201. DOI: 10.1016/j.crsust.2022.100201

⁴² Forrester J. W. *Industrial dynamics*. Cambridge, MA : MIT Press, 1961.

⁴³ Sterman J. D. *Business dynamics: systems thinking and modeling for a complex world*. Boston : Irwin/McGraw-Hill, 2000.

Table 3 (Continued)

<i>Criterion</i>	<i>LCA (attributional / consequential)</i>	<i>MCDM (AHP, TOPSIS, VIKOR)</i>	<i>System dynamics (SD)</i>
Impact coverage	Broad: categories selected at the goal and scope stage from a documented LCIA method (e.g., CML-IA or the Environmental Footprint methods)	Selective: determined by the chosen criteria set; may include social and economic dimensions	Dynamically integrated: resource flows, emissions, feedbacks between subsystems
Standardisation, methodological basis and tools	ISO 14040:2006 ¹³ ; ISO 14044:2006 ¹⁴ ; Environmental Footprint methods; may support EU Taxonomy screening where life-cycle evidence is required	No single standard; AHP after Saaty ¹⁵ ; TOPSIS after Hwang and Yoon ¹⁶	Methodology of Forrester ¹⁷ and Sterman ¹⁸ ; Vensim, AnyLogic
Fit for transition economies	Limited: scarce verified local inventories introduce systematic deviation	High: flexible under incomplete and aggregated data; adaptive criteria selection	Moderate: requires stable series; armed conflict substantially constrains application in Ukraine
Relevance to agri-food systems	Quantifies the environmental burden of renewable technologies; critical for Agri-PV and bioenergy	Compares alternatives across landscape, social and regulatory criteria	Models long-term sectoral development; learning and regulatory feedback loops
Resource intensity	High: ecoinvent/GaBi licences; 3–6 months for a full analysis	Moderate: 1–3 months depending on criteria and stakeholder numbers	High: 3–12 months; a team of 3–5 systems modellers

Source: developed by the author on the basis of⁴⁴.

⁴⁴ Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / ed. by P. R. Shukla et al. Cambridge ; New York : Cambridge University Press, 2022. DOI: 10.1017/9781009157926 ; Pohekar S. D., Ramachandran M. Application of multi-criteria decision making to sustainable energy planning : a review. *Renewable and Sustainable Energy Reviews*. 2004. Vol. 8. № 4. P. 365–381. DOI: 10.1016/j.rser.2003.12.007 ; Strantzali E., Aravossis K. Decision making in renewable energy investments : a review. *Renewable and Sustainable Energy Reviews*. 2016. Vol. 55. P. 885–898. DOI: 10.1016/j.rser.2015.11.021 ; Guinée J. B. (ed.). Handbook on life cycle assessment: operational guide to the ISO standards. Dordrecht : Kluwer Academic Publishers, 2002. DOI: 10.1007/0-306-48055-7 ; Forrester J. W. Industrial dynamics. Cambridge, MA : MIT Press, 1961 ; Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*. 2021. L 471. P. 1–396. URL: <https://eur-lex.europa.eu/eli/reco/2021/2279/oj> ; European Commission, Joint Research Centre. Environmental Footprint methods. URL: <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html> ; Environmental management – Life cycle assessment – Principles and framework. Geneva : International Organization for Standardization, 2006 ; ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. Geneva : International Organization for Standardization, 2006 ; Sterman J. D. Business dynamics: systems thinking and modeling for a complex world. Boston : Irwin/McGraw-Hill, 2000.

Table 3 shows why method choice is context-dependent: LCA is standardised but inventory-intensive, MCDM is flexible but weight-sensitive, and SD is strategically valuable but dependent on sufficiently stable time series.

3. The Decision Framework and Its Application

Principles and structure. The framework rests on the *fit-for-purpose* principle: the choice of approach should follow from the analytical objective, data availability and regulatory context, not from disciplinary convention or tool availability. It treats renewable energy in agri-food systems as a complex socio-ecological system (SES) of biophysical, economic and governance interactions.

It is a structured, rule-based selection framework rather than a fully formalised model: it orders and documents the reasoning behind a method choice without replacing that reasoning with computation. Three analytically distinct but interacting parameters are evaluated in sequence.

The procedure evaluates three parameters sequentially: data quality (I_1), assessment purpose (I_2), and regulatory and institutional context (I_3). Their branch conditions and corresponding methodological outputs are specified in Figure 3 and Table 4.

Resolution rule. Where the signals from $I_1 - I_3$ conflict, priority belongs to the approach explicitly required by the applicable regulatory or financing instrument. Where that instrument calls for life-cycle evidence, LCA becomes the preferred method. Where data constraints make a fully representative LCA impracticable, the procedure directs the analyst to a transitional hybrid combining MCDM with environmental indicators derived through an appropriate LCIA method within a transparent proxy-based or streamlined LCA using adapted or proxy LCI datasets, together with explicit documentation of the resulting limitations. Adapted or proxy LCI datasets are defined here as geographically or technologically adjusted secondary inventory datasets derived from transparent source inventories and accompanied by an explicit assessment of their geographical, temporal and technological representativeness, assumptions and uncertainty. They are a transitional solution where verified national life cycle inventory data are unavailable or insufficiently representative for the relevant processes, and they are not substitutes for comprehensive country-specific LCI inventories.

The framework is advisory rather than algorithmic: it admits variation with context and data quality, and permits hybrid approaches where $I_1 - I_3$ conflict. Figure 3 sets out the logic of the three-step procedure.

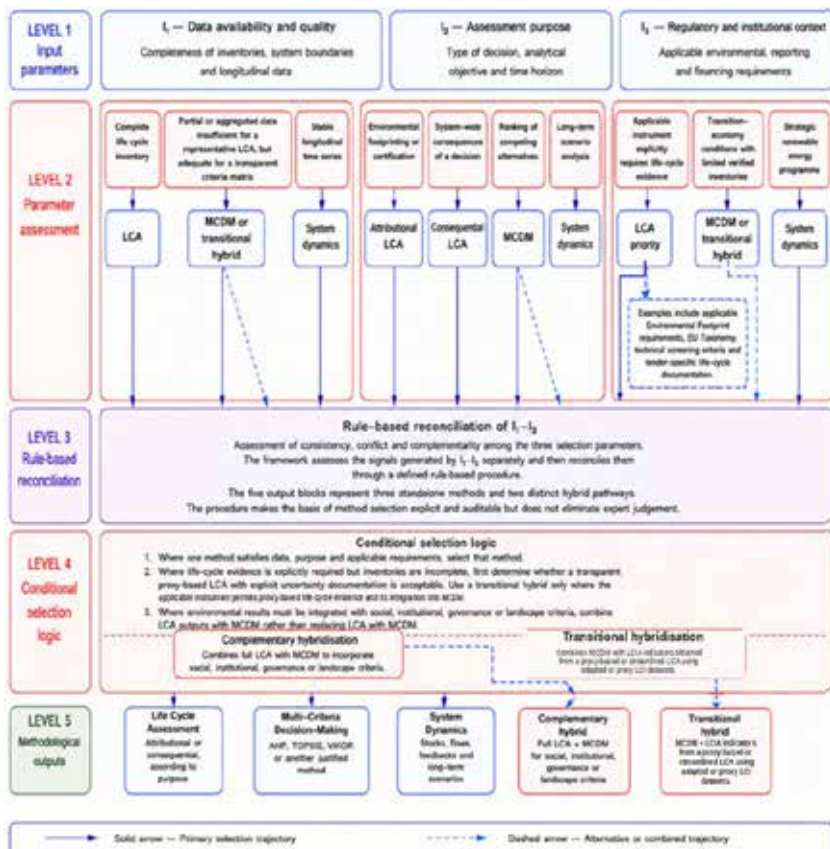


Fig. 3. Structured method-selection framework based on three analytically distinct input parameters – data availability and quality (I₁), assessment purpose (I₂), and regulatory and institutional context (I₃) – followed by rule-based reconciliation into five methodological outputs: LCA, MCDM, SD, complementary hybridisation, and transitional hybridisation. Solid arrows indicate primary selection trajectories; dashed arrows indicate alternative or combined trajectories

Source: developed by the author

The sequence reduces but does not eliminate expert judgement: it makes the basis of method selection explicit, auditable and open to review.

The decision matrix. To make the procedure operational, the three-step logic is systematised as a decision matrix (Table 4), which maps situational characteristics onto recommended approaches.

Table 4

Decision matrix for selecting a methodological approach to renewable energy assessment in agri-food systems

<i>Step</i>	<i>Parameter</i>	<i>Situational characteristic</i>	<i>Recommended method</i>	<i>Complementary assessment or integration</i>
1	I1: data quality	Complete material and energy inventories across the value chain; LCA type determined	LCA (attributional or consequential according to purpose)	LCA + MCDM for post-processing of social criteria
1	I1: data quality	Partial or aggregated data, insufficient for a representative LCA but adequate for a transparent criteria matrix	MCDM or transitional hybrid	MCDM + LCIA indicators from a proxy-based or streamlined LCA using adapted or proxy LCI datasets
1	I1: data quality	Longitudinal data sufficient for calibration and validation of the SD model	SD	SD + simplified LCA for steady-state verification
2	I2: purpose	Environmental certification; Environmental Footprint-compliant assessment; access to green finance	Attributional LCA	LCA evidence used within activity-specific EU Taxonomy screening
2	I2: purpose	Analysis of the systemic consequences of renewable programmes or agricultural bioenergy	Consequential LCA	Consequential LCA + SD for the long-term context
2	I2: purpose	Ranking of competing alternatives; support for a public decision	MCDM	MCDM + DPSIR as the criteria structure
2	I2: purpose	Strategic scenario analysis over a 15–50 year horizon	SD	SD + integrated assessment models
3	I3: regulatory context	A compliance or financing instrument specifying life-cycle evidence	Attributional LCA	LCA + MCDM for management criteria
3	I3: regulatory context	Transition-economy setting with limited institutional and inventory capacity	The method required by the assessment purpose, with transparent proxy data, staged assessment or a transitional hybrid where necessary	Transitional hybrid where appropriate
3	I3: regulatory context	Strategic renewable energy programme for agri-food systems	SD	SD + MCDM in iterative scenario-selection cycles
Output	–	Conflicting signals across I1–I3 → priority to the approach specified by the applicable instrument; where impracticable → transitional hybrid	Transitional hybrid: MCDM with LCIA indicators obtained from a proxy-based or streamlined LCA using adapted or proxy LCI datasets	Documentation of the uncertainty range is a necessary condition of correct application

Source: developed by the author. Notation: attributional LCA – average-impact orientation, basis of the Environmental Footprint methods; consequential LCA – system-consequence orientation; MCDM – multi-criteria decision-making; SD – system dynamics; transitional hybrid – MCDM with LCIA indicators obtained from a proxy-based or streamlined LCA using adapted or proxy LCI datasets

Originality of the framework. The framework's claim to originality rests on four departures from existing methodological reviews: first, its stepwise structure uses three analytically distinct but interacting parameters to exclude unsuitable methods sequentially and replace holistic judgement with documented, auditable inference, whereas earlier comparative reviews⁴⁵ merely set the methods side by side. Second, it treats the attributional – consequential distinction as an independent choice dimension, whereas most reviews collapse LCA into one category – a simplification with material consequences because the variants answer different questions and are not interchangeable for either regulatory or analytical purposes. Third, agri-food specificity – Agri-PV allocation and bioenergy accounting – and the European integration context enter the selection logic directly rather than as external caveats; frameworks developed for construction materials⁴⁶ or waste management⁴⁷ transfer the integration principle but not these domain constraints. Fourth, hybrid combinations are supported explicitly: while existing work presents hybridisation as a design choice, this procedure derives it from diagnosed conditions and identifies when a hybrid is an appropriate output rather than a compromise.

Illustrative application. Two hypothetical Ukrainian cases – a 3 MW agrivoltaic installation and a 0.5 MW biogas plant – use secondary data and assumed project parameters to illustrate the sequential evaluation of $I_1 - I_3$ (Table 5), demonstrating the selection logic rather than providing empirical validation. Because no complete decision matrix or criterion weights were constructed, no formal sensitivity analysis was performed; empirical applications should vary the weights systematically and report both baseline and perturbed rankings.

The cases show that a financing requirement can determine the required orientation of life-cycle evidence for Agri-PV, while insufficient representative inventories direct the assessment to a transitional hybrid rather than a full standalone attributional LCA. By contrast, comparison of community alternatives under limited data favours MCDM, with simplified attributional LCA used only as a complementary assessment. For biogas, results remain conditional on LCA orientation, digestate allocation, functional unit, system boundary, substrate

⁴⁵ Pohekar S. D., Ramachandran M. Application of multi-criteria decision making to sustainable energy planning : a review. *Renewable and Sustainable Energy Reviews*. 2004. Vol. 8. № 4. P. 365–381. DOI: 10.1016/j.rser.2003.12.007 ; Strantzali E., Aravossis K. Decision making in renewable energy investments : a review. *Renewable and Sustainable Energy Reviews*. 2016. Vol. 55. P. 885–898. DOI: 10.1016/j.rser.2015.11.021

⁴⁶ Mlybari E. A. Smart sustainability in construction: an integrated LCA–MCDM framework for climate-adaptive material selection in educational buildings. *Sustainability*. 2025. Vol. 17. № 21. Article 9650. DOI: 10.3390/su17219650

⁴⁷ Integrating life cycle assessment and multi criteria decision making for sustainable waste management: key issues and recommendations for future studies / A. E. Torkayesh et al. *Renewable and Sustainable Energy Reviews*. 2022. Vol. 168. Article 112819. DOI: 10.1016/j.rser.2022.112819

composition, methane yield and fugitive emissions; quantifying their effects requires plant-specific models.

Table 5

**Illustrative application to two hypothetical renewable energy projects
in Ukrainian agri-food systems**

<i>Parameter / selection step</i>	<i>Scenario A: Agri-PV, 3 MW (Kharkiv oblast)</i>	<i>Scenario B: Biogas plant, 0.5 MW (Poltava oblast)</i>
I1: data quality	Partial inventories: capacity, panel type (monocrystalline silicon) and site region known; manufacturing-chain LCI limited. Provisional proxy: ecoinvent datasets for Poland	Biogas yield (m ³ per tonne of manure) and substrate composition assumed known; transport and pipeline LCI limited; data insufficient for consequential LCA
I2: purpose	Hypothetical financing condition: the lender requires life-cycle environmental documentation aligned with EU methods	Internal community decision: public tender among competing technologies; MCDM ranking required
I3: regulatory context	Life-cycle evidence specified by the financing instrument → attributional life-cycle evidence required; because representative inventories are insufficient, the conflict with I1 is resolved through a transitional hybrid.	No instrument specifying an LCA type → MCDM methodologically sufficient
Framework output	Transitional hybrid: MCDM combined with environmental indicators derived via LCIA from adapted or proxy LCI datasets within a transparent proxy-based attributional LCA, with documented geographical, temporal and technological representativeness, assumptions and uncertainty.	MCDM across nine criteria (GWP, cost, employment, acceptance, nitrogen cycle, safety, energy independence, subsidy access and risk), with a simplified attributional LCA for GWP used as a complementary assessment.
Treatment of uncertainty	Proxy-related deviation is not quantifiable without a comparative regional inventory analysis and should be reported qualitatively; Agri-PV allocation is not standardised; an uncertainty statement is mandatory	GWP for biogas varies substantially with the accounting convention for avoided methane and with digestate allocation ¹⁹ ; sensitivity analysis of criterion weights is mandatory in any empirical application
Relation to the literature	IPCC AR5 reports median life-cycle GHG emissions of approximately 41–48 g CO ₂ -eq. kWh ⁻¹ for rooftop and utility-scale photovoltaics ²⁰ .	Hybrid MCDM with LCA elements is consistent with the broader renewable-energy decision-making literature ²¹ ; the choice of LCA type for bioenergy is decisive ²² .

Source: developed by the author. Project parameters are hypothetical and serve to illustrate the sequence of the framework. Polish datasets were chosen provisionally as a geographically proximate proxy; their technological and energy-system representativeness for Ukraine remains to be tested. Any empirical application will require data whose geographical, temporal and technological representativeness for the relevant Ukrainian processes is demonstrated

Validity, limitations and conditions of application. The illustrative application must be read against the limitations that define its validity.

On internal validity, two-stage screening under a predefined protocol constrained confirmation bias in source selection, but the absence of an independent second reviewer remains a limitation, as does the lack of any formal quality appraisal or risk-of-bias assessment, which limits the capacity to distinguish the frequency of an approach from the strength of the evidence behind it. Separating attributional from consequential approaches partly controlled LCA variability, and the subjectivity of MCDM would require parallel computation under AHP and TOPSIS with sensitivity analysis in any empirical application.

On external validity, geographical bias limits generalisability, since studies from the EU and the United Kingdom predominate in the sample. The wartime context constrains SD: modelling that covers 2022–2024 must label the wartime scenario explicitly and compute the reconstruction scenario separately. Participatory MCDM under martial law suffers limited stakeholder representativeness, which weakens the reliability of derived weights.

Nor does the sequential structure eliminate expert judgement, which survives at five points at least: deciding whether available data suffice for a given method; classifying the purpose of the assessment; setting criterion weights; selecting proxy datasets; and ranking competing regulatory requirements. What the framework contributes is that each judgement is made at an identified step and can therefore be documented, reviewed and challenged.

Four further limitations condition the framework: the coverage of verified, nationally representative inventories for the Ukrainian energy mix, agriculture, transport and renewable-energy technologies remains incomplete, and this study did not identify a comprehensive nationally coordinated LCI database covering all the required sectors; consequently, proxy datasets may still be necessary, with their geographical and technological representativeness and associated systematic deviation documented explicitly; wartime and post-war uncertainty affects both the energy balance and the production structure; and specific weight sets transfer poorly between contexts even where the selection logic transfers intact.

Revision will be required as broader and more representative Ukrainian LCI datasets become available, if the EU Taxonomy technical screening criteria for renewable energy are updated, if a standardised allocation convention for Agri-PV is established, or as machine-learning-assisted LCA matures.

Integration with complementary analytical traditions. The frameworks applied in earlier work⁴⁸ – DPSIR, SES and landscape metrics – complement LCA, MCDM and SD naturally, and integration operates on four levels. The diagnostic level (DPSIR) identifies drivers, pressures, states, impacts and responses, its components supplying the structure of the MCDM criteria set⁴⁹. The product level (LCA) quantifies the burden of specific technologies, attributionally for regulatory reporting and consequentially for systemic effects. The decision level (MCDM) compares alternatives, with weights derived through the SES framework. The strategic level (SD) represents reinforcing and balancing loops over the 2030–2050 horizon.

Landscape metrics can enter attributional LCA as land use indicators – a point that matters for Agri-PV, where spatial configuration affects landscape connectivity, insect habitat and microclimatic function. A fragmentation index such as patch density (FRAGSTATS) could be incorporated into the land use category of an LCIA method offering a compatible indicator, subject to verification of unit and characterisation consistency.

Practical implications. Implementation should begin with verified, nationally representative Ukrainian LCI datasets for electricity, agriculture, transport and renewable-energy technologies, together with documented market-response assumptions for consequential modelling. Where proxy datasets remain necessary, their geographical, temporal and technological representativeness must be documented explicitly. At regional and enterprise levels, MCDM can support decisions under incomplete data, while SD remains appropriate for strategic modelling provided that wartime and reconstruction regimes are treated separately.

Effective implementation also requires coordinated national data-governance arrangements assigning responsibility for dataset maintenance, methodological quality assurance and periodic revision. Pilot assessments should follow common protocols for metadata, uncertainty reporting and sensitivity analysis to ensure comparability across institutions, regions and financing programmes. Table 6 assigns the corresponding measures to the principal institutional and enterprise actors.

⁴⁸ Пузік В. К., Криштон Є. А. Системний підхід до екологічно збалансованого природокористування: концептуальні моделі, аналітичні рамки та індикатори. *Методологічні підходи та практичне обґрунтування екологічно збалансованого природокористування і шляхи зниження антропогенного навантаження на природні і штучні екосистеми у сфері АПК* : звіт про НДР (остаточний) / Державний біотехнологічний університет. Харків, 2025. Розд. VII. С. 213–244. № держреєстрації 0121U107701. URL: <https://repo.btu.kharkiv.ua/server/api/core/bitstreams/4d9ea1b4-3100-42e0-80f8-f53ff23f8ed5/content>

⁴⁹ Next generation application of DPSIR for sustainable policy implementation / S. A. Carnohan et al. *Current Research in Environmental Sustainability*. 2023. Vol. 5. Article 100201. DOI: 10.1016/j.crsust.2022.100201

Table 6

**Practical recommendations for key actors: green energy
and environmental safety in Ukrainian agri-food systems**

<i>Actor</i>	<i>Problem</i>	<i>Recommended measure</i>	<i>Expected outcome</i>
Universities and research institutes	Insufficient coverage of nationally representative Ukrainian LCI datasets and insufficiently developed market-response assumptions for consequential modelling	Develop nationally representative LCI datasets and consequential modelling assumptions with the EU Joint Research Centre or comparable international bodies	Methodologically sound LCA for renewable projects in agri-food systems; compatibility with European reporting requirements
Ministry of Environmental Protection	MCDM assessments incomparable across studies, owing to divergent criteria sets and algorithms	Standardise a minimum criteria set (≥ 3 environmental, 2 social, 2 economic); require parallel computation and sensitivity analysis	Comparability across studies; scope for meta-analysis and evidence-based programme design
Ministry of Agrarian Policy	No methodological requirements for the environmental assessment of renewable projects in agri-food systems	Write an LCA or MCDM requirement into the conditions of agri-energy grant competitions and support schemes	Higher project quality; exclusion of options carrying concealed environmental burdens
Ministry of Energy	No strategic SD model for recovery of the renewable sector	Build an SD model of renewable development in agri-food systems to 2050 with international energy agencies; label wartime and reconstruction scenarios explicitly	Evidence-based renewable targets; an instrument for post-conflict strategic planning
Agricultural holdings and renewable developers	No standard for voluntary environmental disclosure	Adopt a sectoral reporting standard compatible with European disclosure requirements; publish life-cycle declarations	Access to ESG investors; competitive advantage in European green finance markets

Source: developed by the author on the basis of⁵⁰.

⁵⁰ International Renewable Energy Agency. Renewable capacity statistics 2024. Abu Dhabi : IRENA, 2024. URL: <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024> ; International Energy Agency. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. 2023 Update. Paris : IEA, 2023. URL: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach> ; Пузік В. К., Криштоп Є. А. Системний підхід до екологічно збалансованого природокористування: концептуальні моделі, аналітичні рамки та індикатори. *Методологічні підходи та практичне обґрунтування екологічно збалансованого природокористування і шляхи зниження антропогенного навантаження на природні і штучні екосистеми у сфері АПК* : звіт про НДР (остаточний) / Державний біотехнологічний університет. Харків, 2025. Розд. VII. С. 213–244. № держреєстрації 0121U107701. URL: <https://repo.btu.kharkiv.ua/server/api/core/bitstreams/4d9ea1b4-3100-42e0-80f8-f53ff23f8ed5/content> ; Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 by establishing technical screening criteria. *Official Journal of the European Union*. 2021. L 442. P. 1–349. URL: https://eur-lex.europa.eu/eli/reg_del/2021/2139/oj ; Food and Agriculture Organization of the United Nations. The State of Food and Agriculture 2023: Revealing the true cost of food to transform agrifood systems. Rome : FAO, 2023. DOI: 10.4060/cc7724en

CONCLUSIONS

LCA, MCDM and system dynamics address distinct but complementary decision needs. Their selection should be governed by data quality, assessment purpose and regulatory context rather than methodological convention. The proposed framework makes this choice explicit, distinguishes attributional from consequential LCA, and identifies when standalone methods, complementary integration or transitional hybridisation are warranted.

Agri-food constraints – including Agri-PV allocation, bioenergy system boundaries, digestate treatment and spatial ecological effects – must enter method selection directly. A transitional hybrid is justified only where life-cycle evidence is required but representative inventories are insufficient. Adapted or proxy LCI datasets should then be used within a transparent proxy-based or streamlined LCA, with their geographical, temporal and technological representativeness, assumptions and uncertainty documented explicitly.

The framework remains conceptual and requires validation through Ukrainian case studies based on verified local inventories. Formalisation should define measurement scales and data-sufficiency thresholds for $I_1 - I_3$, rules for reconciling conflicting signals, and procedures for propagating proxy-data uncertainty into MCDM rankings. Further work should integrate dynamic and prospective LCA, SD, GIS and remote sensing with emerging European data infrastructure. The longer-term objective is a computational DPSIR–LCA–MCDM framework in which SD represents strategic feedback and scenario behaviour.

SUMMARY

The monograph chapter develops a structured decision framework for selecting methodological approaches to assessing the environmental safety of renewable energy projects in agri-food systems under transition-economy conditions. It focuses on life cycle assessment (LCA), multi-criteria decision-making (MCDM) and system dynamics (SD), while environmental safety is operationalised across climatic, ecosystem, resource and toxicological dimensions. *The purpose of the study* is to establish an explicit and auditable procedure for choosing an assessment approach according to data quality, assessment purpose and regulatory and institutional context, including a rule for resolving conflicting signals. *Methodology of the study* combines a targeted methodological review reported using the applicable PRISMA 2020 items and flow diagram, structured data coding, descriptive synthesis, comparative analysis and illustrative case application. The review covered peer-reviewed articles and reviews indexed in Scopus and the Web of Science Core Collection and published between 2019 and 2024. Of 512 records identified,

87 peer-reviewed articles and reviews were included in the final analytical sample. *The results* showed that 32 studies (36.8%) were classified in the LCA cluster, 30 (34.5%) in the MCDM cluster, and 25 (28.7%) in the system dynamics and integrated approaches cluster, while only 10 studies (11.5%) explicitly addressed transition-economy contexts. On this basis, a three-parameter, rule-based framework was developed, yielding five methodological outputs: LCA, MCDM, SD, complementary hybridisation and transitional hybridisation. Where the parameters conflict, priority is given to the approach required by the applicable regulatory or financing instrument. Where life-cycle evidence is required but a representative LCA is impracticable because verified national inventory data are unavailable or insufficient for the relevant processes, a transitional hybrid combining MCDM with LCIA indicators derived from adapted or proxy life cycle inventory datasets is recommended, with explicit documentation of assumptions and uncertainty. The framework is illustrated through hypothetical agrivoltaic and biogas projects in Ukraine; these cases demonstrate the selection logic but do not constitute empirical validation. *Practical implications.* The framework can support environmental policy, renewable-energy planning, green-finance appraisal and enterprise-level decision-making by converting implicit professional judgement into a documented and reviewable procedure. *Value/originality.* The originality of the study lies in structuring method selection as a sequential diagnostic process, treating the attributional–consequential LCA distinction as an independent choice dimension, incorporating agri-food-specific allocation and system-boundary problems directly into the decision logic, and deriving hybridisation from diagnosed assessment conditions rather than assuming it in advance. The framework remains conceptual and requires further formalisation and empirical validation using verified local data.

Bibliography

1. International Renewable Energy Agency. Renewable capacity statistics 2024. Abu Dhabi : IRENA, 2024. URL: <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>
2. International Energy Agency. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. 2023 Update. Paris : IEA, 2023. URL: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>
3. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / ed. by P. R. Shukla et al. Cambridge ; New York : Cambridge University Press, 2022. DOI: 10.1017/9781009157926

4. Chatzipanagi A., Taylor N., Jaeger-Waldau A. Overview of the potential and challenges for agri-photovoltaics in the European Union. Luxembourg : Publications Office of the European Union, 2023. EUR 31482 EN. DOI: 10.2760/208702
5. Pohekar S. D., Ramachandran M. Application of multi-criteria decision making to sustainable energy planning : a review. *Renewable and Sustainable Energy Reviews*. 2004. Vol. 8. № 4. P. 365–381. DOI: 10.1016/j.rser.2003.12.007
6. Strantzali E., Aravossis K. Decision making in renewable energy investments : a review. *Renewable and Sustainable Energy Reviews*. 2016. Vol. 55. P. 885–898. DOI: 10.1016/j.rser.2015.11.021
7. Life cycle assessment and techno-economic analysis of sustainable bioenergy production : a review / A. I. Osman et al. *Environmental Chemistry Letters*. 2024. Vol. 22. № 3. P. 1115–1154. DOI: 10.1007/s10311-023-01694-z
8. Guinée J. B. (ed.). Handbook on life cycle assessment: operational guide to the ISO standards. Dordrecht : Kluwer Academic Publishers, 2002. DOI: 10.1007/0-306-48055-7
9. Laurent A., Olsen S. I., Hauschild M. Z. Limitations of carbon footprint as indicator for environmental sustainability and LCA-based screening tools. *Environmental Science & Technology*. 2012. Vol. 46. № 8. P. 4100–4108. DOI: 10.1021/es204163f
10. Lulovicova A., Bouissou S. Life cycle assessment as a prospective tool for sustainable agriculture and food planning at a local level. *Geography and Sustainability*. 2024. Vol. 5. № 2. P. 251–264. DOI: 10.1016/j.geosus.2024.01.008
11. Пузік В. К., Криштоп Є. А. Системний підхід до екологічно збалансованого природокористування: концептуальні моделі, аналітичні рамки та індикатори. *Методологічні підходи та практичне обґрунтування екологічно збалансованого природокористування і шляхи зниження антропогенного навантаження на природні і штучні екосистеми у сфері АПК : звіт про НДР (остаточний) / Державний біотехнологічний університет. Харків, 2025. Розд. VII. С. 213–244. № держреєстрації 0121U107701. URL: <https://repo.btu.kharkiv.ua/server/api/core/bitstreams/4d9ea1b4-3100-42e0-80f8-f53ff23f8ed5/content>*
12. Forrester J. W. Industrial dynamics. Cambridge, MA : MIT Press, 1961.
13. Armstrong A., Ostle N. J., Whitaker J. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*. 2016. Vol. 11. № 7. Article 074016. DOI: 10.1088/1748-9326/11/7/074016
14. Enhancing ecosystem services and biodiversity in agrivoltaics through habitat-enhancing strategies / A. Ludzuweit et al. *Renewable and*

Sustainable Energy Reviews. 2025. Vol. 212. Article 115380. DOI: 10.1016/j.rser.2025.115380

15. Long-term application of biogas digestate improves soil physical properties / M. Mayerová et al. *Soil and Tillage Research*. 2023. Vol. 231. Article 105715. DOI: 10.1016/j.still.2023.105715

16. Recycling of biogas digestates in plant production: NPK fertilizer value and risk of leaching / T. A. Sogn et al. *International Journal of Recycling of Organic Waste in Agriculture*. 2018. Vol. 7. P. 49–58. DOI: 10.1007/s40093-017-0188-0

17. Digestate in replacement of synthetic fertilisers: a comparative 3-year field study of the crop performance and soil residual nitrates in West-Flanders / G. Reuland et al. *European Journal of Agronomy*. 2024. Vol. 161. Article 127380. DOI: 10.1016/j.eja.2024.127380

18. Short- and long-term impacts of anaerobic digestate spreading on earthworms in cropped soils / V. Moinard et al. *Applied Soil Ecology*. 2021. Vol. 168. Article 104149. DOI: 10.1016/j.apsoil.2021.104149

19. European Commission. Directorate-General for Environment. Guidance document on wind energy developments and EU nature legislation. Luxembourg : Publications Office of the European Union, 2020. DOI: 10.2779/095188

20. Harris Z. M., Spake R., Taylor G. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy*. 2015. Vol. 82. P. 27–39. DOI: 10.1016/j.biombioe.2015.05.008

21. A review of the impacts of Short Rotation Coppice cultivation on water issues / I. Dimitriou et al. *Landbauforschung*. 2009. Vol. 59. № 3. P. 197–206.

22. Dedicated biomass crops can enhance biodiversity in the arable landscape / A. J. Haughton et al. *GCB Bioenergy*. 2016. Vol. 8. № 6. P. 1071–1081. DOI: 10.1111/gcbb.12312

23. Landscape metrics and land-use patterns of energy crops in the agricultural landscape / X. Xu et al. *BioEnergy Research*. 2023. Vol. 16. P. 2178–2191. DOI: 10.1007/s12155-023-10584-9

24. Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 by establishing technical screening criteria. *Official Journal of the European Union*. 2021. L 442. P. 1–349. URL: https://eur-lex.europa.eu/eli/reg_del/2021/2139/oj

25. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*. 2021. L 471. P. 1–396. URL: <https://eur-lex.europa.eu/eli/reco/2021/2279/oj>

26. European Commission, Joint Research Centre. Environmental Footprint methods. URL: <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>
27. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews / M. J. Page et al. *BMJ*. 2021. Vol. 372. Article n71. DOI: 10.1136/bmj.n71
28. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement / D. Moher et al. *PLoS Medicine*. 2009. Vol. 6. № 7. Article e1000097. DOI: 10.1371/journal.pmed.1000097
29. Tighnavard Balasbaneh A., Aldrovandi S., Sher W. A systematic review of implementing multi-criteria decision-making (MCDM) approaches for the circular economy and cost assessment. *Sustainability*. 2025. Vol. 17. № 11. Article 5007. DOI: 10.3390/su17115007
30. Mlybari E. A. Smart sustainability in construction: an integrated LCA–MCDM framework for climate-adaptive material selection in educational buildings. *Sustainability*. 2025. Vol. 17. № 21. Article 9650. DOI: 10.3390/su17219650
31. A critical review of life cycle assessment of renewable agricultural systems / M. Kiehadrouinezhad et al. *Sustainable Energy Technologies and Assessments*. 2025. Vol. 73. Article 104100. DOI: 10.1016/j.seta.2024.104100
32. Establishing the limitations of sustainable construction in developing countries: a systematic literature review using PRISMA / O. E. Ogunmakinde et al. *Smart and Sustainable Built Environment*. 2024. Vol. 13. № 3. P. 609–624. DOI: 10.1108/SASBE-10-2022-0223
33. Integrating life cycle assessment and multi criteria decision making for sustainable waste management: key issues and recommendations for future studies / A. E. Torkayesh et al. *Renewable and Sustainable Energy Reviews*. 2022. Vol. 168. Article 112819. DOI: 10.1016/j.rser.2022.112819
34. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / ed. by O. Edenhofer et al. Cambridge ; New York : Cambridge University Press, 2014. DOI: 10.1017/CBO9781107415416
35. Dec K. Life cycle assessment of renewable energy sources – key issues. Bibliometric analysis of the literature. *Economics and Environment*. 2024. Vol. 89. № 2. Article 839. DOI: 10.34659/eis.2024.89.2.839
36. ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. Geneva : International Organization for Standardization, 2006.
37. ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. Geneva : International Organization for Standardization, 2006.

38. International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment – Detailed guidance / European Commission, Joint Research Centre, Institute for Environment and Sustainability. First edition. Luxembourg : Publications Office of the European Union, 2010. EUR 24708 EN. DOI: 10.2788/38479
39. Ekvall T., Weidema B. P. System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment*. 2004. Vol. 9. № 3. P. 161–171. DOI: 10.1007/BF02994190
40. Saaty T. L. The analytic hierarchy process: planning, priority setting, resource allocation. New York : McGraw-Hill, 1980.
41. Hwang C.-L., Yoon K. Multiple attribute decision making: methods and applications. Berlin ; Heidelberg : Springer, 1981. DOI: 10.1007/978-3-642-48318-9
42. Next generation application of DPSIR for sustainable policy implementation / S. A. Carnohan et al. *Current Research in Environmental Sustainability*. 2023. Vol. 5. Article 100201. DOI: 10.1016/j.crsust.2022.100201
43. Sterman J. D. Business dynamics: systems thinking and modeling for a complex world. Boston : Irwin/McGraw-Hill, 2000.
44. Food and Agriculture Organization of the United Nations. The State of Food and Agriculture 2023: Revealing the true cost of food to transform agrifood systems. Rome : FAO, 2023. DOI: 10.4060/cc7724en

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