Periodica Polytechnica Mechanical Engineering, 69(4), pp. 296–308, 2025

A Review of the Necessity of Improved Life Cycle Inventory Data Quality in Evaluating Renewable Fuels Supported by a Case Study of Recycled Carbon Fuels

Orsolya Ibolya Szalainé Kaczkó[1], Edit Cséfalvay[1], Viktória Barbara Kovács[1*]

[1] Department of Energy Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary

[*] Corresponding author, e-mail: kovacs@energia.bme.hu

Received: 20 March 2025, Accepted: 08 September 2025, Published online: 31 October 2025

Abstract

Climate change is the most significant environmental challenge facing the world today. The EU is implementing various strategies to create a legislative and proposal framework for its Member States, promoting environmental sustainability through the European Green Deal. The EU aims to make Europe the first climate-neutral continent, requiring significant reductions in greenhouse gas (GHG) emissions from the energy sector, including initiatives under the Clean Energy Transition prioritizing renewable fuels. Besides weather-dependent renewables – aligned with waste management regulations – waste-based fuels like recycled carbon fuels (RCFs) can also aid the transition when the 70% GHG emission saving criterion is fulfilled, which is highly dependent on the accuracy of the input data. Digitalization will help higher renewable energy integration, but the extensive use of data requires preserving high privacy, safety, and security standards. Systematic literature research identified blockchain-based systems as an appropriate choice for advanced data collection. Data from a Hungarian municipal solid waste sorting facility was used to investigate the effect of data accuracy on GHG emission saving results of a RCF, comparing the EU regulated calculation method and the holistic life cycle assessment (LCA) method suitable for analyzing complex systems, complemented with a sensitivity analysis. Results showed that the GHG emission saving increases by 4.5 percent points using LCA compared to the EU regulated method. The sensitivity analysis proved the necessity of accurate data as a 1% change of input parameters resulted in a maximum two-fold relative change in GHG emission savings.

Keywords

LCA, blockchain, recycled carbon fuel, waste-to-energy

1 Introduction

Climate change and environmental degradation in EU and all over the world are an existential threat. Green transitions (GT) foster welfare and well-being through a new sustainable economic model, while ensuring socio-economic systems remain within the nine ecological planetary boundaries [1], from which six are crossed by 2023 [2].

An integrated systems approach, promoted by the European Green Deal (EGD) [3], will transform the EU into a modern, resource-efficient and competitive economy. The Regulation (EU) 2021/1119 European Climate law (ECL) is the hearth of EDG setting the net greenhouse gas (GHG) emissions reduction at least 55% by 2030 compared to 1990 levels and ensuring no net emissions of GHGs by 2050 [4].

The production and use of energy account for more than 75% of the EU's GHG emissions. Clean Energy Transition (CET) by increasing the share of renewable energy across the different sectors thus decarbonizing the EU's energy system plays critical role to reach the climate objectives by 2030 and carbon neutrality by 2050 [1, 5].

The Renewable Energy Directive (EU) 2018/2001 (REDII) is the legal framework for CET across all sectors of the EU economy, supporting cooperation between EU countries towards the goals since 2018 setting the renewable target to 32% by 2020 [6]. To speed up the EU's clean energy transition the REDII was revised in 2023. The amending Directive (EU) 2023/241 elevated the overall renewable energy target at least 42.5%, aiming for 45%, binding at EU level by 2030 [7].

Ensuring a secure and affordable renewable based EU energy supply a fully integrated, interconnected [5] and digitalized [8] EU energy market need to be developed where

Cite this article as: Szalainé Kaczkó, O. I., Cséfalvay, E., Kovács, V. B. "A Review of the Necessity of Improved Life Cycle Inventory Data Quality in Evaluating Renewable Fuels Supported by a Case Study of Recycled Carbon Fuels", Periodica Polytechnica Mechanical Engineering, 69(4), pp. 296–308, 2025. https://doi.org/10.3311/PPme.40487

electricity becomes the key carrier, providing a cost-efficient way to decarbonize our energy use, either through directly or indirectly, for example through hydrogen generation based on electrolysis. However, electrification is not always the most efficient decarbonization solution, it should be complemented by decarbonized solutions of heating and cooling based on renewable- or waste heat [5].

Digitalization will aid in higher renewable energy integration, thus enable decarbonization with more connected, intelligent, efficient, reliable and sustainable energy systems using information and communication technologies (ICT), modern sensors, big data and artificial intelligence, and the internet of things (IoT) technologies, which connecting the physical and digital worlds [8]. The extensive use of data requires preserving high privacy, security, safety, and ethical standards, particularly for cyber security matters. Distributed ledger technologies (DLTs) and blockchain (BC) can be potential solutions for these addressed issues [9–13]. To reach the full potential of digitalization, the EU is accelerating the development and uptake of these advanced technologies, among others, launched the European Blockchain Partnership (EBP) in 2018 to develop an EU strategy on BC and deploy the European Blockchain Services Infrastructure (EBSI).

However, the digitalization will have potentially significant benefits on the energy sector, due to the increased data exchange is likely to entail higher energy consumption of the ICT sector, therefore its energy efficiency and its climate impact should be addressed as well [8].

The Energy Efficiency Directive (EED) is a key driver of CET as energy efficiency helps reduce overall energy consumption thus achieving EU's climate ambition, while enhancing energy security and affordability [14]. To ensure the EU's GHG emission reduction goal can be met by 2030, the EED was amended in 2018 and 2023. The first amendment (Directive (EU) 2018/2002 [15]) established a binding energy efficiency target for reduction in final energy consumption (FEC) of at least 32.5% by 2030 compared to 2007 and required EU countries to draw up integrated 10-year national energy and climate plans (NECPs) for the 2021–2030 period with an obligatory update in 2023 [15]. The updated Hungarian NECP increased the EU approved minimum 40% GHG emission reduction to 50%, the 21% of renewable energy share in FEC to 30%; and the energy efficiency target is to ensure that the country's FEC should be reduced by 6% compared to 2021, which is by 5.7% higher compared to the original commitment [16, 17].

The second revision of EED (Directive (EU) 2023/1791 [18]) established the 'energy efficiency first' principle obligations and set an additional binding 11.7% reduction in FEC by compared to 2020 and elevated the obligatory annual FEC savings to 1.3%, 1.5%, 1.9% in 2024–2025, 2026–2027 and 2028–2030, respectively [18]. Moreover, this revised EED also introduced an obligation to monitor and report the energy performance of data centers, and the Commission Delegated Regulation (EU) 2024/1364 [19] set the key indicators of data centers.

As the EU phases out fossil fuels biomass-based renewable fuels (including biodegradable fraction of waste, which has to be collected separately in the EU by the end of 2023 set by the Directive 2008/98/EC [20] Waste Framework Directive (WFD) amended by Directive (EU) 2018/851 in 2018 [21]), renewable fuels of non-biological origin (RFNBOs); and recycled carbon fuels (RCFs) produced from non-recyclable waste of non-renewable origin may also have a significant role by lowering the EU's external energy dependence, while contributing to GHG mitigation. REDII set targets for increasing share of RFNBOs, based mainly on renewable hydrogen (H_2) produced *via* electrolysis [22], reaching at least 42% of all H_2 used in industry by 2030, and 60% by 2035. However, these fuels should fulfill the sustainability and GHG emission saving criteria set by REDII to be accounted as renewable and thus contribute to renewable energy shares. GHG emissions saving should be at least 50–80% for biomass-based fuels depending on application and 70% for RFNBOs and RCFs compared to fossil fuels. The GHG accounting should be based on a life cycle assessment (LCA) methodology and consider indirect emissions [7]. Environmental Footprint (EF) is the EC recommended methodology [23]. REDII for biomass-based fuels and the Commission Delegated Regulation (EU) 2023/1185 [24] on GHG emissions of RFNBOs and RCFs describes the calculation methodology for GHG emission saving aided by the Commission Implementing Regulation (EU) 2022/996 [25] (IR) which contains the standard GHG emission factors [25]. However, other sources of emission factors can be used such as the latest version of the JEC-WTW report, the Ecoinvent database, IPCC, IEA or other reviewed sources such as the E3 and GEMIS database and peer reviewed publications, if the input is not included in the regulations [24, 25].

The EU's transition to a circular economy is a prerequisite to achieving the 2050 climate neutrality. Europe's new agenda for sustainable growth, the new circular economy action plan (CEAP), one of the main building blocks of EGD, was adopted in 2020 [26]. CEAP announced initiatives along the entire life cycle of products targeting how products are designed, promotes circular economic processes, encourages sustainable consumption, and aims to ensure that waste is prevented, and the resources used are kept in the EU economy for as long as possible, thus reducing natural resource use while providing sustainable growth.

The Regulation (EU) 2024/1781 [27] Ecodesign for Sustainable Products Regulation (ESPR) align with CEAP significantly improve the sustainability of products placed on the EU market by improving their circularity, energy performance, recyclability and durability; establishes a framework for setting ecodesign requirements on specific product groups; and introduce Digital Product Passport (DPP), a digital identity card for products, components, and materials, which will store relevant information, such as technical product's performance, materials and their origins, repair activities, recycling capabilities, and lifecycle environmental impacts based on LCA methodology, to support products' sustainability, promote their circularity and strengthen legal compliance. This information shall be accessible electronically aiding more informed decisions [27]. DPP represents a significant advance in product transparency and sustainability fostering a more open and responsible marketplace by integrating BC-based open data principles with accessible and standardized data will enhance the visibility and integrity of product information, benefiting companies, consumers, and the environment.

The applicability of BC/DLT technologies for DPP was tested in the first cohort of the EU Blockchain Sandbox, which showed the potential of these solutions for DPPs and formed the basis for deeper dives and additional regulatory topics which will be discussed in the next cohorts [28].

2 Systematic literature review on BC enhanced LCA

The EU's strict environmental policy and digitalization efforts require increasingly large and specific data-intensive LCA, which necessitates the use of DLT/BC technologies.

Therefore, a systematic literature review was conducted to identify the state of the art on research of BC application in LCA.

Ten searches were conducted using the built-in Artificial Intelligence search engine in Scopus database. The used terms were:

1. Block-chain opportunities in LCA.
2. Blockchain-based LCA system architecture.
3. Blockchain-based LCA framework.
4. LCA block-chain.
5. How does blockchain technology ensure transparency and traceability in LCA processes?
6. How can blockchain technology be used to verify the accuracy and reliability of data in LCA processes?
7. Blockchain usage in conducting LCA-s related to energy generation.
8. What are the potential challenges of integrating blockchain into LCA practices?
9. How can blockchain technology improve transparency in LCA processes?
10. How does blockchain technology impact the accuracy and reliability of LCA data collection?

The generative AI tool created a short summary and an expanded summary of each topic. These results are based on 67 separate sources, which included original scientific articles, review articles, conference proceedings and book chapters. Most of them are conference proceedings (28), followed by original articles (21) and book chapters (11). Some of the identified sources have been excluded due to unavailability (especially in case of book chapters) or language other than English. The Scopus AI searches have been complemented with separate searches in Scopus Database recently.

During the literature review, several common points were identified, with the aim of answering the following research questions:

1. What function can BC technology fulfill in the field of LCA (detailed in Section 2.1)?
2. What infrastructure is needed to integrate the technology (detailed in Section 2.1)?
3. What are the difficulties that may arise during the implementation (detailed in Section 2.2)?

The identified database elements were checked, and sorted out based on different aspects and criteria, that can be seen on Fig. 1 based on PRISMA 2020 [29].

2.1 BC functions and infrastructure

BC technology originated in the financial sector, particularly in the field of cryptocurrencies. It is based on a decentralized and distributed registry of interconnected data blocks, which are secured by cryptographic techniques [30]. The BC system consists of connected nodes that can record and transfer data between existing blocks and new ones added with every transaction. Whenever a node executes a transaction or a product departs from the facility, BC technology can be used to document crucial

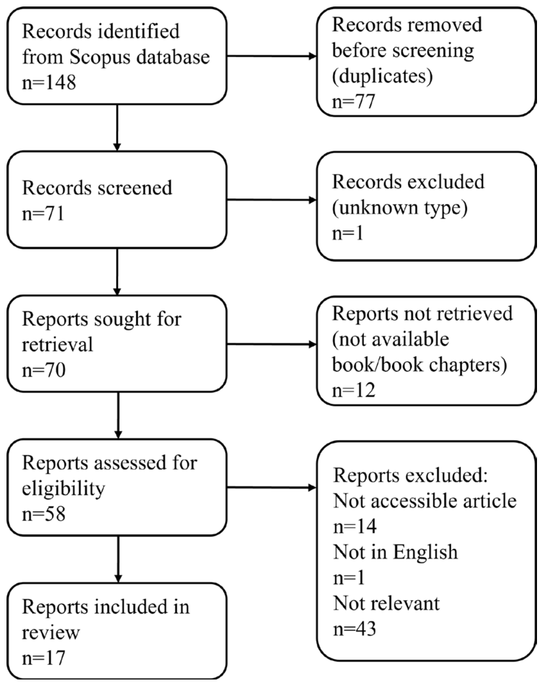

Fig. 1 Flow diagram of literature review based on PRISMA 2020 [29]

information regarding the product's nature, quality, quantity, location, and ownership. Each recorded transaction is encrypted and includes a timestamp that indicates when the specific production phase occurred or when a new transaction was added. Once the information is recorded, it is verified and digitally signed by all parties involved, ensuring its security and immutability [31].

The BC system can offer valuable support during the data collection and inventory analysis phases of LCA if integrated properly. The BC-based LCA system that will be developed consists of five layers: a stakeholder layer, a product system layer, a BC information system layer, an LCA database and software layer, and a user layer [32].

Supply chain activities can account for up to 90% of the environmental impact of companies involved in product processing [33]. BC technology offers numerous advantages in supply chains, which today operate as a complex international network due to technological changes in communication and transport and geographical fragmentation [34]. It can effectively reduce GHG emissions, water usage, and waste generation [30]. Therefore, BC technology could provide a solution for integrating production data and delivering real-time environmental information in the current era of advanced technology, being in fourth generation [35]. Its key features include decentralization, security, auditability, smart contracts [36], immutability, and anonymity [31], making it an effective tool for supporting LCA. This system can significantly reduce fraud, including greenwashing [37].

Current issues in LCAs include inefficient data transmission, lack of available data, and concerns regarding data security [37]. The implementation of BC addresses issues in LCA related to quantitative data on material and energy consumption in production processes [38]. Making the life cycle of products transparent through BC technology can help reduce waste generation in manufacturing processes [36] and improve recyclability by providing detailed composition information [39]. A BC-aided holistic and integrated life cycle sustainability assessment (HILCSA) framework has been developed to facilitate rapid and secure data sharing, which differs from traditional LCSA framework in data gathering. This framework automatically computes impact assessment results and transparently communicates these findings to decision-makers [35], serving as a decision support tool [40] that identifies environmental hotspots and quantifies circular potential [39]. The precise data obtained through this approach enhances the granularity and representativeness of impact characterization compared to generic data from databases like Ecoinvent and LCA for Experts, and aids in identifying the most critical production stages [33].

Transparency encourages all stakeholders to act more cautiously regarding their impact on sustainability [41] and should be integrated into design processes [42]. For instance, a QR code can provide customers with current environmental information about the product [30]. Additionally, this technology can improve the Emission Trading System (ETS), support green energy transformation and energy resilience [31], and promote the development of transactive energy systems. With the help of BC technology, distributed household energy generation can be monitored and controlled more efficiently [43].

BC is also a key enabler for achieving sustainable development goals (SDGs), as it plays a significant role in:

1. Building resilient and transparent supply chains;
2. Creating substantial and accountable public institutions;
3. Promoting responsible sourcing and consumption [35].

It can improve building utilization patterns by minimizing uncertainties and maximizing transparency regarding the impact of user decisions. Currently, the methodologies for assessing the sustainability of built assets, such as LCA, lack the thoroughness needed to achieve a cradle-to-cradle cycle and provide a comprehensive decision-making platform [41]. Furthermore, secondary markets can be enhanced by BC to promote reuse schemes [39], and the technology can support the development of a sharing economy, as usage fees can be determined based on traceable records [44].

Current issues in LCAs include inefficient data transmission, a lack of available data, and concerns about data security [37]. The use of BC technology addresses other LCA challenges related to the quantitative data on material and energy consumption during production processes [38].

The frameworks and mandatory steps outlined in the ISO 14040:2006 and ISO 14044:2006 standards [45, 46] can be streamlined through the use of BC technology. This approach improves transparency and traceability during the goal and scope definition phase, allowing experts to make more informed decisions. Automated and real-time data collection supports comprehensive inventory analysis, which is the most challenging phase of LCA because complete input data is often unavailable for complex supply chains [31].

Data collection may involve the use of various technologies, such as IoT, RFID [30], and NFC [39]. Additionally, smart meters (including thermometers and flow meters) and optical sensors can enhance the accuracy of data collection [36]. It is essential to link the physical material with its digital identity, which is stored in a BC system. Throughout the supply chain, each manufacturer contributes their data, and at the end of the production phase, a digital ownership certificate is created [39]. It is assumed that companies are willing to share their data for effective operation [37].

In the data processing phase, big data analysis aids experts in their evaluations. The generated specific shared data can replace the generic datasets used in databases like Ecoinvent and LCA for Experts [37]. Furthermore, during the interpretation phase, visualization and trend analysis can be enhanced [36].

BC allows for a more accurate LCA that considers the energy sources used in production, leading to precise calculations of the carbon footprint for products and built assets, especially for renewable energy sources [41]. Additionally, improved data management ensures better end-user access, transaction control, reduced human error, high-quality data, and enhanced information flow and access controls [42].

There are several examples of use in various industries, such as the cobalt mining industry, pharmaceutical industries, agri-food industry [30], Dutch dairy sector [38], forestry, fishery [35], aircraft operation and maintenance [31], fashion industry [39], and textile production [33].

2.2 Challenges in BC implementation

While BC technology offers many benefits, its adoption faces significant challenges. The lack of a uniform data collection framework [47] across different industries complicates data transfer and feedback mechanisms [31]. Privacy concerns also arise when data is shared across the BC, highlighting the need for permissioned or federated BCs [48].

In complex product systems, collecting and storing all LCA data necessitates significant storage capacity [36], which can lead to excessive energy consumption, large memory requirements [35], and high upfront costs [48].

Several management and environmental factors make this transition challenging, including a lack of managerial commitment, expertise, and tools for implementing BC technology. Additionally, there may be resistance to change and opposition to data sharing from various stakeholders, alongside insufficient government regulation and lack of involvement from external stakeholders [30]. Striking a balance between transparency and privacy further complicates matters [44].

Moreover, workforce-related issues can present barriers in adopting new technology due to challenges in collaboration, cultural differences [35], and varying digital skills among employees [33]. The nature of the data itself also poses obstacles, including asymmetric distribution, instability in information demand in real-time environments [35], and issues with convertibility [43].

3 Material and methods

To investigate the effect of data accuracy on the environmental performance of renewable fuels municipal solid waste (MSW) was considered as the source of renewable fuel production, because:

- The separate collection of biodegradable fraction of MSW set by REDII enhances the production of biogas used in combined heat and power generation (CHP) or upgraded to biomethane as according to the RePowerEU plan [49] and its implementation [50] sustainable biomethane must be waste-based.
- The non-renewable fraction of MSW that is not suitable for material recovery in accordance with WFD is considered as relevant energy input for RCFs production.

Further investigations were made with RCF production based on our previous study [51] on a Hungarian waste-to-energy (WtE) facility.

3.1 Evaluation of RCF

According to RED II and the EU/2023/1185 [24] Delegated Regulation the minimum GHG emission savings from using of RCFs shall be at least 70% to be able to account RCFs in renewable energy targets [7, 24].

GHG emissions from the manufacture of machinery and equipment shall not be considered.

Besides CO_2, N_2O and CH_4 must be taken into account for calculating GHG emission, with 1, 298; and 25 g CO_{2eq}/g GHG, respectively.

GHG emission from the production and use of RCFs is calculated in Eq. (1):

$$E = e_i + e_p + e_{td} + e_u + e_{ccs}, \quad (1)$$

where E is the total GHG emission from the use of RCF (g CO_{2eq}/MJ fuel), $e_i = e_{i,elastic} + e_{i,rigid} + e_{ex-use}$ is the GHG emissions from supply of inputs; $e_{i,elastic}$ is the emissions from elastic inputs; $e_{i,rigid}$ is the emissions from rigid inputs; e_{ex-use} is the emissions from inputs' existing use or fate; e_p is the emissions from processing; e_{td} is the emissions from transport and distribution, e_u is the emissions from combusting the fuel in its end-use; e_{ccs} is the emission savings from CO_2 capture and geological storage; all expressed in g CO_{2eq}/MJ_{fuel}.

GHG emission saving from RCF as transport fuel is calculated in Eq. (2):

$$S = \frac{(E_F - E)}{E_F}, \quad (2)$$

where S is the GHG emission saving; E is the total emissions from the use of RCF, and E_F is the total emissions from the fossil fuel comparator, which shall be 94 g CO_{2eq}/MJ.

Based on the fossil fuel comparator and the GHG saving criteria the life-cycle GHG emission of RCFs should be less than 28.2 g CO_{2eq}/MJ.

However, it is assumed that RCF is used in a CHP unit, where heat is co-generated with electricity. In this case the emissions shall be allocated between heat and electricity, irrespective if the heat is used for actual heating purposes based on Annex VI of RED II [7, 52]. GHG emissions from the use of RCF in CHP unit including the energy conversion to electricity and heat, expressed in g $CO_{2eq}/MJ_{\text{final energy}}$, shall be calculated as follows:

1. For the electricity coming from CHP unit:

$$EC_{el} = E/\eta_{el} \cdot \left[C_{el} \cdot \eta_{el} / \left(C_{el} \cdot \eta_{el} + C_h \cdot \eta_h\right)\right]. \quad (3)$$

2. For the useful heat coming from CHP unit:

$$EC_h = E/\eta_h \cdot \left[C_h \cdot \eta_h / \left(C_{el} \cdot \eta_{el} + C_h \cdot \eta_h\right)\right]. \quad (4)$$

In Eqs. (3) and (4) EC_{el} and EC_h are the total GHG emission from the final energy commodity; E is the total GHG emission of the fuel before end-conversion; η_{el} is the electrical efficiency, defined as the annual electricity produced divided by the annual energy input, based on its energy content; η_h is the heat efficiency, defined as the annual useful heat output divided by the annual energy input, based on its energy content; C_{el} is the fraction of exergy in the electricity, and/or mechanical energy, set to 100% (C_{el} = 1); C_h is the Carnot efficiency (fraction of exergy in the useful heat), defined as:

$$C_h = \left(T_h - T_0\right)/T_h, \quad (5)$$

where T_h is the temperature of the useful heat at point of delivery (K); T_0 is 273.15 K.

GHG emission saving from electricity and heat generated from biogas or biomethane is calculated in Eq. (6):

$$S = \left(EC_{F,\text{CHP}} - EC_{B,\text{CHP}}\right)/EC_{F,\text{CHP}}, \quad (6)$$

where S is the GHG emission saving; $EC_{B,\text{CHP}}$ is the total emission from the heat and electricity; $EC_{F,\text{CHP}}$ is the total emission from the fossil fuel comparator for useful heat and electricity, which shall be 80 g CO_{2eq}/MJ for heat production and 183 g CO_{2eq}/MJ for electricity generation.

Based on the fossil fuel comparators and the GHG saving criteria of the life-cycle GHG emissions of biogas or biomethane applied in CHP units should be less than 16–36.6 g CO_{2eq}/MJ depending on the share of produced heat and electricity.

3.2 LCA

RED II and the EU/2023/1185 [24] Delegated Regulation provides the methodology for GHG emission savings criteria for the evaluation of RCFs, but this methodology is simplified, considering only three GHG gases. Therefore, an LCA model was also created to compare the simplified results with the ones obtained from the most effective waste management evaluation tool, which provides the most quantitative information for comparing competitive technologies [53].

Although LCA framework is standardized, with four main phases [45], the LCA results depend on, e.g., scopes, assumptions, system boundaries, models, impact assessment methodologies, and datasets, that should be chosen appropriately and applied to the investigated WtE system during the LCA phases:

1. Goal and Scope Definition, detailed in Section 3.2.1.
2. Life Cycle Inventory Analysis (LCI), presented in Section 3.2.2.
3. Life Cycle Impact Assessment (LCIA), discussed in Section 3.2.3.
4. Interpretation, presented in Section 3.2.4.

The LCIA results and their interpretation can be seen in Sections 4.2 and 4.3.

3.2.1 Goal and scope

The primary task is to define the aim and system boundary of the LCA study and precisely define the function of the system with the associated functional unit. In this case the goal was to provide a comparative environmental evaluation based on GHG emission extended with sensitivity analysis on RCF CHP utilization produced from the non-recyclable share of mixed municipal solid waste (MMSW) that is sorted in a Hungarian Municipal Recovery Facility (MRF) based on our previous study [51] applying different scope and system boundary (Fig. 2).

Based on the energy efficiency factor (R1) of WtE systems [54–56], introduced by WFD and its Hungarian implementation (43/2016. (VI. 28.) FM Decree) [54], among the previously investigated CHP units ICE was chosen as it provides the highest R1 for the WtE system, namely 0.72, with coke utilization.

From this paper's perspective, CHP utilization of RCF is the main function. Align with the requirements of RED II and the EU/2023/1185 [24] Delegated Regulation, any further co-products (coke) or co-services (crediting electricity and heat) were excluded from the investigation applying energy content-based allocation. The manufacture of machinery and equipment of RCF production and use were also excluded.

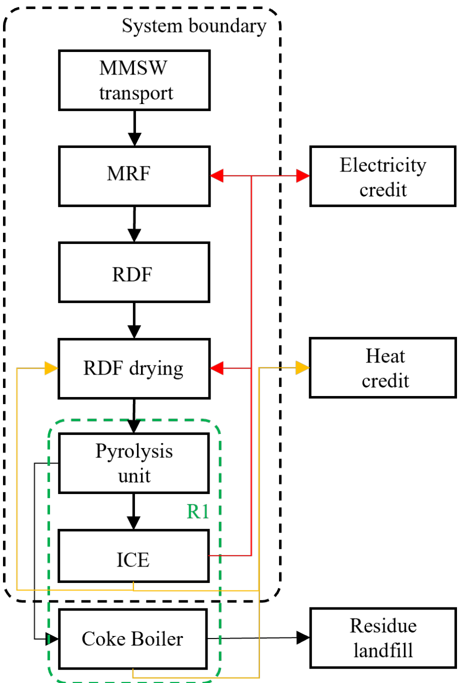

Fig. 2 System boundary of WtE system with RCF production and utilization

As the produced RCF amount and quality depend on the system's parameters, the functional unit is the collected MSW from the micro-region of the investigated WtE system in a year, which is 40,000 t.

The LCA model was created in the LCA for experts 10.9 Product Sustainability Software environment with its Professional database version 2024. For determining the GHG emissions associated with RCF, the EF 3.1 impact assessment method was used.

3.2.2. LCI

To determine the environmental impacts, it is necessary to assess and quantify the material-, energy requirements, and waste streams of the RCF considering the functional unit and allocate to RCF using the energy content based allocation factor.

The measured material and energy-related input data of the collected MMSW and MRF is included in Table 1 [51].

The initial moisture content of the RDF was 40%, which was reduced to 20% in a dryer. The RCF data are included in Table 2 [51]. The yield and composition-based heating value of RCF were determined from measurements and mass balance. The CO_2 emission of RCF combustion was determined from its carbon content. The other emission values were determined from the calculated annual flue gas amount and the average emission value listed in [57, 58].

Table 1 LCI–material and energy-related input data [51]

Input	Unit	Initial value	Range
MSW, wet	t/a	40,000	
MSW transport	km	35	20–50
RDF, wet fraction	m/m%	33.5	20–45
RDF biogenic fraction	m/m%	46	
$\text{Moisture}_{\text{RDF,wet}}$	m/m%	40	30–50
MRF, electric demand	kW	450	
Dryer, thermal demand	$\text{MJ/kg}_{\text{H2O}}$	3	
Pyrolysis unit, electric	$\text{MJ/kg}_{\text{,RDF}}$	1.44	
RCF, dry fraction	m/m%	50	40–60
ICE, electric efficiency	%	38	35–45
ICE, thermal Efficiency	%	40	40–50

Table 2 LCI–input data of RCF [51]

	Unit	RCF
Yield	m/m%	0.7
LHV	MJ/kg	15.2
Amount	t/a	7,025
CO_2 emission	t/a	9,330
TOC emission	kg/a	81.3
N_2O emission	kg/a	129.7
Allocation factor	–	0.68

3.2.3 LCIA

Impact assessment methods use scientific models to systematize and clarify complex environmental impacts, allowing the identification of the simultaneous impact of multiple pollutants and the hotspots of the environmental impacts.

EF3.1 midpoint impact assessment method [23, 59] recommended by the European Commission was selected as this method is compatible with the available software and databases (LCA for experts professional).

The LCA framework is standardized by ISO 14040:2006 [45] and ISO 14044:2006 standards [46], and the LCIA includes some mandatory steps like classification and characterization. In the first step the EF3.1 assigns the inventory elements of an LCA model to 25 EFs, each with its own unit [60]. In this study only the climate change (GWP) impact category, expressed in kg CO_{2eq}, was analyzed. In the characterization step, the magnitude of GWP was determined from the inventory data using the characterization model associated with GWP [59].

3.2.4 Interpretation

The results obtained should be examined to see if they match the goal and scope of the study; if not, the model needs to be refined, while the conclusions drawn from the results were put into a form that is understandable to the target audience.

The LCA based GWP and GHG emission saving of RCF production and use were determined to compare with the GHG emission saving calculated form the default emission factors in RED II and the Delegated Regulation (EU) 2023/1185 [24] .

But LCIA results can be highly uncertain in waste management evaluations. This is due to the combined effects of data variability, measurement errors, incorrect estimations, unrepresentative or missing data, and modeling assumptions. Three systematic methods for assessing uncertainty of waste management LCA results have been developed [61]:

- Sensitivity analysis: determine the effect of changes in input data on LCIA result.
- Uncertainty propagation: calculating the uncertainty in the model results caused by all input uncertainties.
- Uncertainty contribution analysis: show where output uncertainties come from.

Since this research is aimed to demonstrate the impact of input values on the results rather than analyze the model's reliability, only the sensitivity analysis was carried out, considering the changes in the LCI input parameters listed in Table 1.

Two indicators can be used to demonstrate sensitivity [61]. The firs one in Sensitivity Coefficient (SC), which shows the rate between the absolute change of the result (r) and the parameter (p), calculated in Eq. (7):

$$\mathrm{SC} = \Delta r / \Delta p . \tag{7}$$

The second one, the Sensitivity Ratio (SR), shows the relative change in the input, and the result calculated in Eq. (8):

$$\mathrm{SR} = \left(\Delta r / \text{initial } r\right) / \left(\Delta p / \text{initial } p\right). \tag{8}$$

In this study SR was used, due to the different dimensions of the LCI input data and results. Sensitivity analysis aids in identifying the input parameters that should be refined to reduce the uncertainties of the LCIA results effectively.

4 Results

GHG emission saving results of RCF production and CHP utilization according to 1185/2023 [24] Delegated Regulation is presented in Section 4.1. GWP and GHG emission savings of RCF based on the LCA model presented in Section 3.2.1 are detailed in Section 4.2. The sensitivity analysis results on the effect of changing LCI data is presented in Section 4.3.

4.1 GHG emission saving of RCF

The GHG emission (E) for RCF production resulted in 51.85 g CO_{2eq}/MJ RCF using Eq. (1) by applying the default emission factors listed in Annex C of Delegated Regulation (EU) 2023/1185 [24] and Annex III of RED II for transport diesel oil (95.1 g CO_{2eq}/MJ fuel), and waste combustion (91.7 g CO_2/MJ fuel for non-renewable, and 0 g CO_2/MJ fuel for biomass origin, 0.004 g N_2O/MJ fuel, and 0.03 g CH_4/MJ fuel).

Considering the 94 g CO_{2eq}/MJ fossil fuel comparator in Eq. (2), the GHG saving (S) for RCF production is only 44.8%, which is far from the desired 70%; thus, this fuel could not be accounted for the renewable targets.

If RCF is utilized in ICE for heat and power generation the GHG emissions according to Eqs. (3) to (5). are 96.2 g CO_{2eq}/MJ for electricity and 38.2 g CO_{2eq}/MJ for heat. Based on Eq. (6). the obtained slightly improved GHG saving values are still far from the desired 70%, only 47.4% and 52.2% for electricity and heat, respectively.

4.2 LCIA of RCF

Fig. 3 shows the GWP of annual production and ICE utilization of RCF. In the initial case is 5,113 t CO_{2eq} considering MMSW transport, and RCF combustion. The

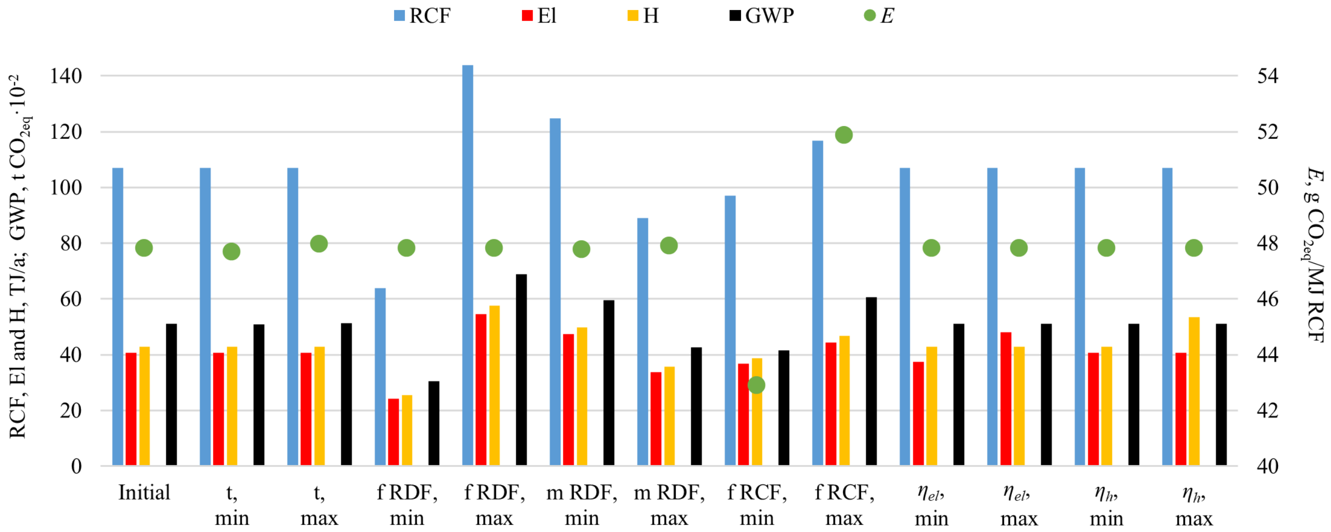

Fig. 3 RCF potential, electricity (El) and heat (H) production; GWP and E results for RCF production and utilization, considering the changes in the input parameters

GHG emission for the energy content of RCF (E) presented in Fig. 4 was calculated from GWP and the annual RCF potential (106.9 TJ/a) resulting to 47.82 kg CO_{2eq}/MJ, which is by 7.7% lower and the GHG emission saving (S) is 49.1% that is by 4.3 percentage points higher compared to the ones obtained in Section 4.1.

With the ICE utilization the GHG emissions for the final products are 88.7 g CO_{2eq}/MJ for electricity and 35.2 g CO_{2eq}/MJ for heat that are by 7.8% lower compared to the values resulting in 51.5% and 55.9% GHG emission savings for electricity and heat, respectively.

Fig. 3 represents the effect of the changes in the LCI input parameters between their maximum and minimum value on the annual RCF potential, electricity (El) and heat (H) production, and the resulting GWP and E. However, the relative standard deviation (RSD) of RCF, El, H and GWP are around 18%, but RSD for E is only 4% and some of the input parameters do not have significant effect on any of the results, such as transport distance (t) or the electric and thermal efficiencies (η_{el}, η_h) of ICE. Other parameters like RDF wet fraction (f RDF) and RDF moisture content (m RDF) have significant effect on RCF, El and H, but practically no effect on E. Only RCF dry fraction (f RCF) has significant effect on all the investigated parameters.

4.3 Sensitivity analysis

To identify which input parameter has a relevant effect on the GHG emission saving that evaluates the RCF the SR was calculated according to Eq. (8) based on the LCIA results presented in Fig. 3 and obtained applying the changes in the parameters in Table 1. The corresponding GHG emission savings for RCF production (S) and for ICE utilization generating electricity (S_{el}) and heat (S_h) as well as the GHG emissions from the production and use of RCF (E) and for the final product (electricity, heat) of RCF use in ICE (EC_{el}, EC_h). The SRs greater than 0.1 in absolute value were visualized on Fig. 4 to help identify the input parameters to which the different E and S results are sensitive [61].

EC_{el} and EC_h had the same value when changing the input parameters due to their calculation method; therefore, they were visualized together as $EC_{el,h}$. Only SRs of f RCF, η_{el} and η_h parameter changes reached the limit of 0.1 in absolute value. Alterations in η_h seemed to have

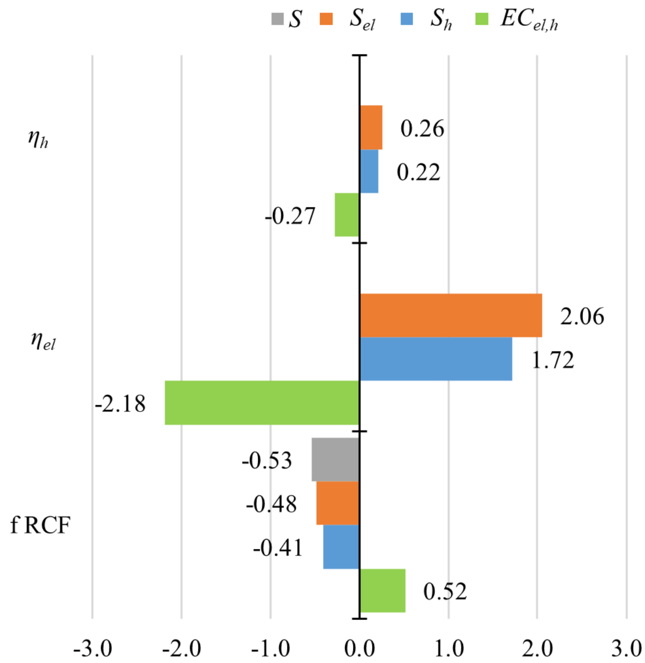

Fig. 4 SRs regarding GHG emissions and savings

minimal effects on the results, as SR of EC_{el}, EC_h, S_{el} and S_h were below 0.3, and zero for S, which is the same in the case of η_{el} changes. The modification of f RCF resulted in minor SRs, with below 0.6 absolute values.

The most outstanding SRs are related to the change of η_{el}, with a maximum absolute value higher than two for EC_{el}, EC_h, and S_{el} meaning 5% change in electricity efficiency resulted more than 10% change in GHG emission saving of electricity production from RCF.

5 Conclusions

The EU GT with its legislation on renewable energy and waste was reviewed, highlighting the importance of digitalization that leads to improved data-gathering technologies. With a systematic literature review, BC was identified as an excellent solution for LCI data quality improvement.

The importance of BC in LCA was verified by our own analysis using data from a Hungarian MSW sorting facility to determine the effect of data accuracy on GHG emission saving results of a RCF, comparing the EU-regulated calculation method for RCFs and the holistic LCA method suitable for analyzing complex systems, complemented with a sensitivity analysis.

Our results showed that the GHG emission (E) decreased by 7.7% and the GHG emission saving (S) increased by 4.3 percent points using LCA compared to the EU regulated method, which could be reduced by more specific GHG emission data employed by EU regulations. The sensitivity analysis showed that a 1% change in input parameters resulted in a maximum two-fold relative change in GHG emission savings. This proves the importance of better data gathering practices, which can be assisted by BC technology, that was identified by the systematic literature review as an efficient tool in improving transparency thus allowing more reliable environmental assessments.

Acknowledgement

Viktória Barbara Kovács was supported by the "Parents Back to Science" scholarship ("Vissza a Tudományba! ösztöndíj") of the BME.

Orsolya Szalainé-Kaczkó was supported by the Doctoral Excellence Fellowship Programme (DCEP) is funded by the National Research Development and Innovation Fund of the Ministry of Culture and Innovation and the Budapest University of Technology and Economics.

References

[1] European Commission "Shaping the green transitions for a sustainable and fair Europe", Publications Office of the European Union, 2023. ISBN 978-92-76-99825-9 https://doi.org/10.2760/03344

[2] Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., …, Rockström, J. "Earth beyond six of nine planetary boundaries", Science Advances, 9(37) eadh2458, 2023. https://doi.org/10.1126/sciadv.adh2458

[3] European Commission "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal: COM/2019/640 final", Brussels, Belgium, 2019. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52019DC0640 [Accessed: 30 August 2025]

[4] The European Parliament and the Council of the European Union "Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')", Brussels, Belgium, 2021. [online] Available at: https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng [Accessed: 30 August 2025]

[5] European Commission "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Powering a climate-neutral economy: An EU Strategy for Energy System Integration: COM/2020/299 final", Brussels, Belgium, 2020. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0299 [Accessed: 30 August 2025]

[6] The European Parliament and the Council of the European Union "Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.)", Brussels, Belgium, 2018. [online] Available at: https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng [Accessed: 30 August 2025]

[7] The European Parliament and the Council of the European Union "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652", Brussels, Belgium, 2023. [online] Available at: https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng [Accessed: 30 August 2025]

[8] European Commission "Commission Staff Working Document: Accompanying the document: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Digitalising the energy system - EU action plan: SWD/2022/341 final", Brussels, Belgium, 2022. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022SC0341 [Accessed: 30 August 2025]

[9] Nai Fovino, I., Andreadou, N., Geneiatakis, D., Giuliani, R., Kounelis, I., Lucas, A., Marinopoulos, A., Martin, T., Poursanidis, I., Soupionis, I., Steri, G. "Blockchain in the Energy Sector", Publications Office of the European Union, Gare Luxembourg, Luxembourg, Rep. EUR 30782 EN, 2021. https://doi.org/10.2760/061600

[10] The European Parliament "European Parliament resolution of 3 October 2018 on distributed ledger technologies and blockchains: building trust with disintermediation (2017/2772(RSP))", Brussels, Belgium, 2017. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=oj:JOC_2020_011_R_0003 [Accessed: 30 August 2025]

[11] The European Parliament and the Council of the European Union "Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast) (Text with EEA relevance)", Brussels, Belgium, 2019. [online] Available at: https://eur-lex.europa.eu/eli/reg/2019/943/oj/eng [Accessed: 30 August 2025]

[12] The European Parliament and the Council of the European Union "Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast) (Text with EEA relevance.)", Brussels, Belgium, 2019. [online] Available at: https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng [Accessed: 30 August 2025]

[13] The European Parliament and the Council of the European Union "Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 as regards improving the Union's electricity market design (Text with EEA relevance)", Brussels, Belgium, 2024. [online] Available at: https://eur-lex.europa.eu/eli/dir/2024/1711/oj/eng [Accessed: 30 August 2025]

[14] The European Parliament and the Council of the European Union "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance", Brussels, Belgium, 2012. [online] Available at: https://eur-lex.europa.eu/eli/dir/2012/27/oj/eng [Accessed: 30 August 2025]

[15] The European Parliament and the Council of the European Union "Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance.)", Brussels, Belgium, 2018. [online] Available at: https://eur-lex.europa.eu/eli/dir/2018/2002/oj/eng [Accessed: 30 August 2025]

[16] Ministry of Innovation and Technology "National Energy and Climate Plan", [pdf] Ministry of Innovation and Technology, Budapest, Hungary, 2018. Available at: https://energy.ec.europa.eu/system/files/2022-08/hu_final_necp_main_en.pdf [Accessed: 30 August 2025]

[17] Ministry of Innovation and Technology "National Energy and Climate Plan: 2024 update", [pdf] Ministry of Innovation and Technology, Budapest, Hungary, 2024. Available at: https://commission.europa.eu/document/download/0a2953f8-5789-4f6f-9714-03df3d-4cbbab_en?filename=HU_FINAL%20UPDATED%20NECP%202021-2030%20%28English%29.pdf [Accessed: 30 August 2025]

[18] The European Parliament and the Council of the European Union "Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) (Text with EEA relevance)", Brussels, Belgium, 2023. [online] Available at: https://eur-lex.europa.eu/eli/dir/2023/1791/oj/eng [Accessed: 30 August 2025]

[19] European Commission "Commission Delegated Regulation (EU) 2024/1364 of 14 March 2024 on the first phase of the establishment of a common Union rating scheme for data centres", Brussels, Belgium, 2024. [online] Available at: https://eur-lex.europa.eu/eli/reg_del/2024/1364/oj/eng [Accessed: 30 August 2025]

[20] The European Parliament and the Council of the European Union "Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)", Brussels, Belgium, 2008. [online] Available at: https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng [Accessed: 30 August 2025]

[21] The European Parliament and the Council of the European Union "Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance)", Brussels, Belgium, 2018. [online] Available at: https://eur-lex.europa.eu/eli/dir/2018/851/oj/eng [Accessed: 30 August 2025]

[22] European Commission "Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin", Brussels, Belgium, 2023. [online] Available at: https://eur-lex.europa.eu/eli/reg_del/2023/1184/oj/eng [Accessed: 30 August 2025]

[23] European Commission "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", Brussels, Belgium, 2021. [online] Available at: https://eur-lex.europa.eu/eli/reco/2021/2279/oj/eng [Accessed: 30 August 2025]

[24] European Commission "Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels", Brussels, Belgium, 2023. [online] Available at: https://eur-lex.europa.eu/eli/reg_del/2023/1185/oj/eng [Accessed: 30 August 2025]

[25] European Commission "Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria (Text with EEA relevance)", Brussels, Belgium, 2022. [online] Available at: https://eur-lex.europa.eu/eli/reg_impl/2022/996/oj/eng [Accessed: 30 August 2025]

[26] European Commission "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A new Circular Economy Action Plan For a cleaner and more competitive Europe: COM/2020/98 final", Brussels, Belgium 2020. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0098 [Accessed: 30 August 2025]

[27] The European Parliament and the Council of the European Union "Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC (Text with EEA relevance)", Brussels, Belgium, 2024. [online] Available at: https://eur-lex.europa.eu/eli/reg/2024/1781/oj/eng [Accessed: 30 August 2025]

[28] European Commission "European Blockchain Sandbox: Best practices report: 1st Cohort, Part B", Publications Office of the European Union, Gare Luxembourg, Luxembourg, Rep. KK-06-24-099-EN-N, 2024. https://doi.org/10.2759/76203

[29] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., …, Moher, D. "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews", BMJ, 372, 71, 2021. https://doi.org/10.1136/bmj.n71

[30] Carrières, V., Lemieux, A.-A., Pellerin, R. "Opportunities of Blockchain Traceability Data for Environmental Impact Assessment in a Context of Sustainable Production", In: IFIP International Conference on Advances in Production Management Systems, Nantes, France, 2021, pp. 124–133. ISBN 978-3-030-85874-2 https://doi.org/10.1007/978-3-030-85874-2_13

[31] Asif, M. S., Gill, H. "Blockchain Technology and Green Supply Chain Management (GSCM) – Improving Environmental and Energy Performance in Multi-echelon Supply Chains", IOP Conference Series: Earth and Environmental Science, 952(1), 012006, 2022. https://doi.org/10.1088/1755-1315/952/1/012006

[32] Rolinck, M., Gellrich, S., Bode, C., Mennenga, M., Cerdas, F., Friedrichs, J., Herrmann, C. "A Concept for Blockchain-Based LCA and its Application in the Context of Aircraft MRO", Procedia CIRP, 98, pp. 394–399, 2021. https://doi.org/10.1016/j.procir.2021.01.123

[33] Carrières, V., Lemieux, A.-A., Margni, M., Pellerin, R., Cariou, S. "Measuring the Value of Blockchain Traceability in Supporting LCA for Textile Products", Sustainability, 14(4), 2109, 2022. https://doi.org/10.3390/su14042109

[34] Wittine, Z., Franc, S., Barišić, A. "Blockchain Technology Potential to Transform Global Value Chains", In: International Conference on Decision Support System Technology (ICDSST 2022), Thessaloniki, Greece, 2022, pp. 3–15. ISBN 978-3-031-06530-9 https://doi.org/10.1007/978-3-031-06530-9_1

[35] Tišma, S., Škrtić, M. M. "Blockchain Technology in the Environmental Economics: A Service for a Holistic and Integrated Life Cycle Sustainability Assessment", Journal of Risk and Financial Management, 16(3), 209, 2023. https://doi.org/10.3390/jrfm16030209

[36] Zhang, A., Zhong, R. Y., Farooque, M., Kang, K., Venkatesh, V. G. "Blockchain-based life cycle assessment: An implementation framework and system architecture", Resources, Conservation and Recycling, 152, 104512, 2020. https://doi.org/10.1016/j.resconrec.2019.104512

[37] Lin, X., Li, X., Kulkarni, S., Zhao, F. "The Application of Blockchain-Based Life Cycle Assessment on an Industrial Supply Chain", Sustainability, 13(23), 13332, 2021. https://doi.org/10.3390/su132313332

[38] Karaszewski, R., Modrzyński, P., Müldür, G. T., Wójcik, J. "Blockchain Technology in Life Cycle Assessment—New Research Trends", Energies, 14(24), 8292, 2021. https://doi.org/10.3390/en14248292

[39] Shou, M., Domenech, T. "Integrating LCA and blockchain technology to promote circular fashion – A case study of leather handbags", Journal of Cleaner Production, 373, 133557, 2022. https://doi.org/10.1016/j.jclepro.2022.133557

[40] Farooque, M., Jain, V., Zhang, A., Li, Z. "Fuzzy DEMATEL analysis of barriers to Blockchain-based life cycle assessment in China", Computers & Industrial Engineering, 147, 106684, 2020. https://doi.org/10.1016/j.cie.2020.106684

[41] Shojaei, A., Wang, J., Fenner, A. "Exploring the feasibility of blockchain technology as an infrastructure for improving built asset sustainability", Built Environment Project and Asset Management, 10(2), pp. 184–199, 2020. https://doi.org/10.1108/BEPAM-11-2018-0142

[42] Sunmola, F., Burgess, P. "Transparency by Design for Blockchain-Based Supply Chains", Procedia Computer Science, 217, pp. 1256–1265, 2023. https://doi.org/10.1016/j.procs.2022.12.324

[43] Nepal, J. P., Yuangyai, N., Gyawali, S., Yuangyai, C. "Blockchain-Based Smart Renewable Energy: Review of Operational and Transactional Challenges", Energies, 15(13), 4911, 2022. https://doi.org/10.3390/en15134911

[44] Chen, S., Cai, X., Wang, X., Liu, A., Lu, Q., Xu, X., Tao, F. "Blockchain applications in PLM towards smart manufacturing", The International Journal of Advanced Manufacturing Technology, 118(7), pp. 2669–2683, 2022. https://doi.org/10.1007/s00170-021-07802-z

[45] ISO "ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework", International Organization for Standardization, Geneva, Switzerland, 2006.

[46] ISO "ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines", International Organization for Standardization, Geneva, Switzerland, 2006.

[47] Ahmed, W. A. H., MacCarthy, B. L. "Blockchain-enabled supply chain traceability – How wide? How deep?", International Journal of Production Economics, 263, 108963, 2023. https://doi.org/10.1016/j.ijpe.2023.108963

[48] Song, J. M., Sung, J., Park, T. "Applications of Blockchain to Improve Supply Chain Traceability", Procedia Computer Science, 162, pp. 119–122, 2019. https://doi.org/10.1016/j.procs.2019.11.266

[49] European Commission "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: REPowerEU Plan: COM/2022/230 final", Brussels, Belgium, 2022. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022DC0230 [Accessed: 30 August 2025]

[50] European Commission "Commission Staff Working Document Implementing the RePowerEU Action Plan: Investment needs, hydrogen accelerator and achieving the bio-methane targets: Accompanying the document: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: REPowerEU Plan: SWD/2022/230 final", Brussels, Belgium 2022. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022SC0230 [Accessed: 30 August 2025]

[51] Kovács, V. B., Hidegh, G. T., Rácz, E., Szücs, B., Csókai, V., Józsa, V. "Life cycle assessment of a micro-region Hungarian municipal solid waste: Evaluation of six waste-to-energy scenarios", Energy Conversion and Management, 294, 117568, 2023. https://doi.org/10.1016/j.enconman.2023.117568

[52] ISCC "ISCC EU 205 Greenhouse Gas Emissions, Version 4.1", [pdf] ISCC System GmbH, 2023. Available at: https://www.iscc-system.org/wp-content/uploads/2024/01/ISCC_EU_205_Greenhouse-Gas-Emissions_v4.1_January2024.pdf [Accessed: 30 August 2025]

[53] Christensen, T. H., Damgaard, A., Levis, J., Zhao, Y., Björklund, A., Arena, U., Barlaz, M. A., Starostina, V., Boldrin, A., Astrup, T. F., Bisinella, V. "Application of LCA modelling in integrated waste management", Waste Management, 118, pp. 313–322, 2020. https://doi.org/10.1016/j.wasman.2020.08.034

[54] Ministry of Agriculture "43/2016. (VI. 28.) FM rendelet a hulladékgazdálkodással kapcsolatos ártalmatlanítási és hasznosítási műveletek felsorolásáról" (43/2016. (VI. 28.) FM Decree on the list of disposal and recovery operations in waste management), Budapest, Hungary, 2016. [online] Available at: https://net.jogtar.hu/jogszabaly?docid=a1600043.fm [Accessed: 30 August 2025] (in Hungarian)

[55] European Commission "Guidelines on the interpretation of the R1 Energy efficiency formula for incineration facilities dedicated to the processing of municipal solid waste according to Annex II of Directive 2008/98/EC on Waste", [pdf] European Commission, 2011. Available at: https://ec.europa.eu/environment/pdf/waste/framework/guidance.pdf [Accessed: 30 August 2025]

[56] Viganò, F. "A practical method to calculate the R1 index of waste-to-energy facilities", Waste Management, 73, pp. 287–300, 2018. https://doi.org/10.1016/j.wasman.2017.09.036

[57] Neuwahl, F., Cusano, G., Gómez Benavides, J., Holbrook, S., Roudier, S. "Best Available Techniques (BAT) reference document for waste incineration", Publications Office of the EU, 2019. ISBN 978-92-76-12993-6 https://doi.org/10.2760/761437

[58] Lecomte, T., Ferrería de la Fuente, J. F., Neuwahl, F., Canova, M., Pinasseau, A., Jankov, I., Brinkmann, T., Roudier, S., Delgado Sancho, L. "Best Available Techniques (BAT) reference document for large combustion plants", Publications Office of the EU, 2017. ISBN 978-92-79-74303-0 https://doi.org/10.2760/949

[59] Damiani, M., Ferrara, N., Ardente, F. "Understanding Product Environmental Footprint and Organisation Environmental Footprint methods", Publications Office of the European Union, 2022. ISBN 978-92-76-57214-5 https://doi.org/10.2760/11564

[60] Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., Ardente, F. "Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method", Publications Office of the European Union, Gare Luxembourg, Luxembourg, Rep. EUR 31414 EN, 2023. https://doi.org/10.2760/798894

[61] Clavreul, J., Guyonnet, D., Christensen, T. H. "Quantifying uncertainty in LCA-modelling of waste management systems", Waste Management, 32(12), pp. 2482–2495, 2012. https://doi.org/10.1016/j.wasman.2012.07.008