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Qualitative analysis of the application of BM-LCA in the evaluation of business models for renewable energy communities

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Abstract

This study explores the application of Business Model Life Cycle Assessment (BM-LCA) to evaluate the environmental performance of Renewable Energy Communities (RECs), using the Hitzar REC located in Gipuzkoa (Basque Country, Spain), as a real case study. A novel integration of a Sustainable Business Model Canvas is proposed to enhance the methodology by incorporating a preliminary qualitative assessment of governance and sustainability aspects along with the traditional business model considerations. The analysis focuses on defining a clear value proposition, evaluating environmental and economic flows, and identifying strengths and challenges in the application of BM-LCA to the evaluation of RECs, which has also proven to be a useful tool for systematically identifying the key elements that must be understood when analyzing business models. The study demonstrates how BM-LCA links material and financial flows to sustainability outcomes, enabling informed decision-making processes and contributing to the development of sustainable energy solutions. Additionally, the study highlights the importance of tailoring BM-LCA to address the unique characteristics of RECs, such as their community-oriented governance and dependence on external technical and financial support. These aspects underscore the need for methodological adaptations to better capture the social and economic dimensions of these initiatives. Future work will expand on this framework through the quantitative application of BM-LCA to compare BM configurations and energy management scenarios of different REC models, contributing to the sustainable energy transition.

Keywords

Business model life cycle assessment, Circular business model, Life cycle thinking, Renewable energy communities, Sustainable business model innovation

1.Introduction

Renewable energy generation by community-owned projects has the potential to increase energy efficiency, reduce CO_2 emissions, lower consumers' energy bills, foster the creation of new jobs and promote citizen empowerment, social cohesion, and social equity (Mendoza et al., 2022; Kiamba et al., 2022). Furthermore, energy communities are seen as a key lever for the energy transition (Bellini *et al.*, 2024). The European Commission estimates that by 2030, more than 50 GW of wind energy and over 50 GW of solar energy could be owned by energy communities, representing respectively 17% and 21% of the current installed capacity, respectively (Vernay and Sebi, 2020), while by 2050, almost half of European households are expected to participate in renewable energy generation schemes, 37% of them in collective projects (Kampman *et al.*, 2016; REScoop, 2018).

Renewable Energy Communities (RECs) are increasingly being linked to Sustainable Business Models (SBMs) as they transform traditional energy systems into more decentralized and participatory models (Neri and Corsetti, 2024) On the other hand, REC can provide several sustainability benefits across six Sustainability Development Goals (SDGs) (Ibarra *et al.*, 2023), such as reducing emissions, boosting local economies, enhancing social equity, alleviating energy poverty, and promoting gender equality, (SDG 4, 7, 8, 9, 11, 13). This is why the literature on SBMs for REC has grown in the past few years, particularly from 2019, aligning with the "Clean Energy for All Europeans" package (Cavallaro *et al.*, 2023).

Business models play a crucial role in shaping production-consumption systems and enabling sustainability-driven innovation (Boons & Lüdeke-Freund, 2013a; Lüdeke-Freund & Wever, 2010; Urbinati et al., 2017). SBMs are understood as holistic view on how business is done in relation to its stakeholders, including the society and the natural environment (Bocken, 2023). In this sense, research indicates that the deployment of SBMs can lead to relevant progress in terms of decoupling economic activity from resource consumption and environmental impacts (Das *et al.*, 2022; De Giacomo and Bleischwitz, 2020; van Loon *et al.*, 2021).

Reaching environmental sustainability requires understanding the relations between human actions and material (tangible) flows, which sets the foundation for the sociomaterial perspective on flows (Baumann and Lindkvist, 2022). The sociomaterial approach highlights how institutional arrangements are shaped by the impact certain actors have over others within product chain (Afrane, 2013; Baumann & Lindkvist, 2022). This is of great interest for REC's business models in which the business ecosystem plays an important role (Ibarra et al., 2023). The study from Rabanete et al., (2024) underlines the importance of adaptable, responsive, and community-driven ecosystems in supporting RECs. The socio-material approach was developed by complementing the environmental analysis of flows in product Life Cycle Assessment (LCA), incorporating additional information about actors and networks, and reframing this hybrid study through a socio-material perspective (Lindkvist and Baumann, 2017).

The literature on SBMs has been mainly focused on the environmental assessment of products with different business configurations, with comparatively less focus on the detailed analysis of the business models themselves (Mendoza et al., 2022). Most studies use LCA (ISO, 2006) to compare products associated with different business model scenarios and configurations, such as the rental and sale of clothing (Bech *et al.*, 2019; Johnson and Plepys, 2021) or baby strollers (Kerdlap *et al.*, 2021). Nevertheless, these approaches do not provide a clear evaluation of the environmental performance derived from (or being dependent on) the economic structure of the business models, even when combined LCA and life cycle costing (LCC) studies are performed (Bi *et al.*, 2017; Kaddoura *et al.*, 2019).

Furthermore, academic studies have primarily focused on qualitative aspects, with relatively quantitative approaches providing metrics and indicators to assess the sustainable impact of different business models beyond a non-profit approach, such as REC (Ibarra et al., 2023). As the sustainability of REC's business model is often dependent on external support (e.g., legal, technical, and economic advice), adopting an ecosystem perspective is essential to identify key stakeholders across the value network and understand their roles in supporting the REC's operations (Giehl et al., 2020; Vernay & Sebi, 2020a). Thus, the environmental assessment of SBMs requires the use of robust methodologies integrating economic and environmental business model considerations (Bocken *et al.*, 2016; Harris *et al.*, 2021; Ibarra *et al.*, 2024; Kravchenko *et al.*, 2019), which is the case of the recently developed BM-LCA approach.

BM-LCA (Böckin et al., 2022) is a novel methodology for evaluating the environmental performance of business models (Böckin *et al.*, 2022; Lüdeke-Freund, 2010). Key aspects of BM-LCA include a fundamental shift in the unit of analysis from the product system to the business model itself, using economic performance as the basis for comparison (Böckin *et al.*, 2022; Lüdeke-Freund, 2010). BM-LCA links the financial flows of a business model to the physical flows of a life cycle assessment in a coherent, analytical way and enables analysis for decoupling within business practices which supports business model innovation and helps validate sustainable business models (Böckin *et al.*, 2022). This method can be applied to any business models involving material or resource use, including circular and sustainable business models (Baumann, 2022; Goffetti et al., 2022).

RECs are increasingly linked to innovative business models, transforming traditional energy systems into more decentralized and participatory ones (Neri and Corsetti, 2024). Unlike traditional for-profit business models, RECs focus on community ownership and creating social, environmental, and economic value for their members, rather than prioritizing financial profit. This difference means that BM-LCA needs to be adapted to properly evaluate the sustainability of RECs. Analyzing these differences will strengthen the rationale for this study, highlighting the need to adjust the methodology to fit the specific characteristics of RECs.

Although RECs serve as the specific empirical context of this study, the methodological approach particularly the integration of the SBMC-REC in the BM-LCA framework is intended to be transferable to other sustainability-oriented business models. The unique characteristics of RECs, such as democratic governance and community-driven value creation, make them a valuable case to explore broader insights relevant to mission-driven organizations and socio-technical systems.

The aim of this conference paper is to qualitatively analyze how BM-LCA can be applied in practice to evaluate and improve the sustainability performance of RECs´ business models and, in this process, to define methodological challenges and opportunities for further improvement for the assessment of complex systems. Accordingly, this study attempts to provide a baseline for the development of a clear conceptual framework for the application of BM-LCA to develop SBMs for RECs, serving as a foundation for future research involving a quantitative sustainability assessment, incorporating the business ecosystem perspective. While the study applies BM-LCA to a specific case, its findings are highly relevant for advancing a truly sustainable energy transition, as they provide valuable insights to support the transformation of business models across various economic sectors.

Specifically, the study addresses the following objectives:

1. To qualitatively apply the BM-LCA methodology to a real-world REC case (Hitzar) in order to assess its sustainability performance.
2. To identify methodological and practical challenges in applying BM-LCA to non-profit, community-based business models, and to derive recommendations for further development of the method.

Although not initially defined as a research objective, the integration of the SBMC-REC emerged during the analysis as a helpful tool to structure the “Goal and Scope” phase of BM-LCA, particularly in capturing governance and sustainability dimensions specific to RECs. This contribution is discussed in the results.

2.Method

The methodology (Figure 1) follows a three-step structured approach for the exploration of the application of BM-LCA to the analysis and comparison of different SBM-REC system configurations.

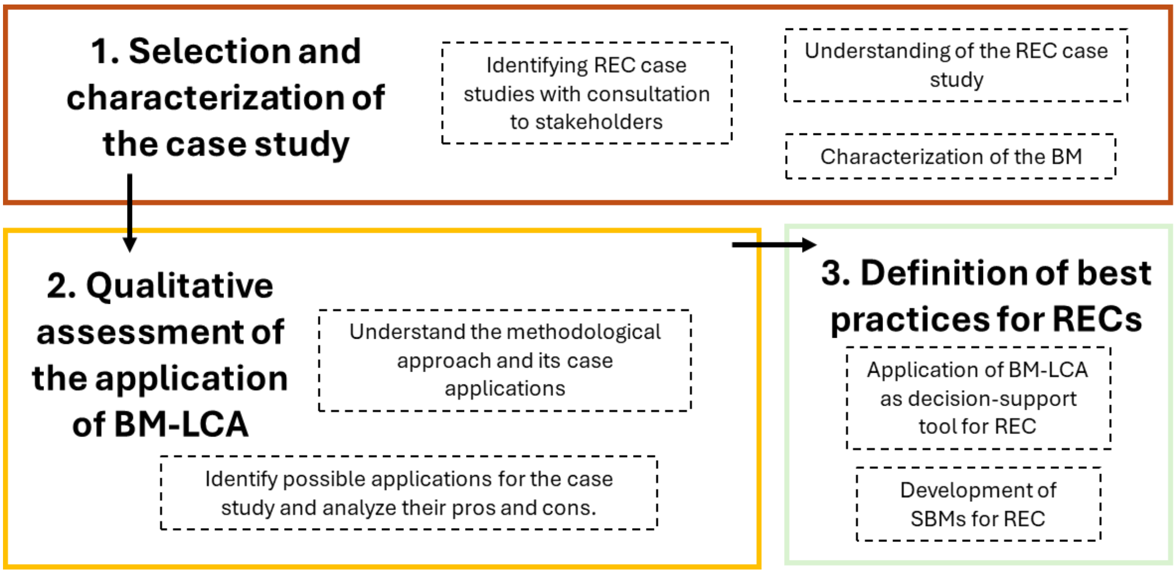

FIG. 1 DESCRIPTIVE OVERVIEW OF THE APPLIED METHODOLOGY ACRONYMS: REC: RENEWABLE ENERGY COMMUNITY; BM: BUSINESS MODEL; BM-LCA: BUSINESS MODEL LIFE CYCLE ASSESSMENT; SBM: SUSTAINABLE BUSINESS MODEL

2.1. Selection and characterization of the case study

The first step of the methodology involves the selection and characterization of a case study. In this study, the REC of Hitzar (HITZAR.Koop. S., 2024) located in Gipuzkoa (Basque Country, Spain) serves as the reference case to explore the qualitative application of BM-LCA (Böckin *et al.*, 2022).

2.1.1 Identifying REC case studies with consultation to stakeholders

The process of identifying RECs in Gipuzkoa involved an in-depth analysis of the approximately 55 REC currently operating in the region. This was conducted using a Participatory Action Research (PAR) approach (Bocken *et al.*, 2018), a collaborative methodology that integrates knowledge and action to drive social transformation (Torre *et al.*, 2015). The PAR approach actively engaged community members, researchers, and stakeholders, leveraging their strengths to identify representative RECs for further study (Collins *et al.*, 2018).

This identification process was enriched by insights gathered during the First Forum of REC in Gipuzkoa (November 2024), where representatives shared the progress, challenges, and achievements of these initiatives (DFG, 2024). The Forum organized by the Transformation Energy Office of Gipuzkoa**,** gathered key stakeholders, including representatives from 25 RECs, officials from the Gipuzkoa Provincial Council (such as the Deputy for Sustainability, the Director of Ecological Transition, and technical staff), and members of the Transformation Energy Office of Gipuzkoa. The forum served as a platform to share experiences, address challenges, and propose collaborative actions to strengthen the development of REC in the region.

As a result of this process, the Hitzar REC (HITZAR.Koop. S., 2024) in Itsasondo was selected as the case study for this research. Hitzar was identified as one of the most developed RECs in the region and recognised as a highly relevant case by key stakeholders involved in the energy community sector. This business case offers a unique opportunity to explore how BM-LCA can be effectively applied to explore the environmental and economic sustainability performance of an ongoing REC in the region of Gipuzkoa (Basque Country, Spain). This is one of the Spanish leading regions in the deployment of REC across the territory, providing valuable insights into its potential for supporting sustainable business model transformation for a sustainable energy transition.

2.1.2 Understanding of the REC case study Hitzar

Hitzar REC is located in Itsasondo, a small village in Gipuzkoa (Basque Country, Spain) with 400 inhabitants. The journey to establish this community began in 2022 with the intention of developing an association. After extensive discussions and collaboration with Goiener, a leading promoter of RECs and a key cooperative in the Basque Country focused on renewable energy development (Goiener, 2025), the initiative evolved into a more robust structure as a Cooperative.

By 2023, the Hitzar REC, a cooperative focused on sustainable energy generation, had grown to 35 members. Goiener stepped back from the project in 2023, leaving Hitzar to lead the development of its first installation; a project, named Iraola, for the implementation of 35 kW solar system. However, Iberdrola, the regional electricity distributor (Ibedrola, 2025), limited the installation's capacity to 10 kW due to transformer restrictions, allowing it to supply energy to only 9 members.

Faced with these constraints, Hitzar redefined its strategy to ensure economic, technical, and voluntary sustainability. After an unsuccessful attempt to collaborate with Goieki, a local economic development agency (Goieki, 2025), they partnered with Biziola, a regional entity dedicated to supporting and promoting sustainable energy projects and community initiatives (Biziola, 2025). Through Biziola’s guidance, Hitzar realized the potential to expand their project regionally in the Goierri area, a region in Gipuzkoa, Basque Country.

By late 2023, Hitzar began work on its second installation, named Lukasain, a 65 kW solar system in Ordizi, which helped grow the cooperative to 70 members by 2024. Hitzar now operates two solar installations:

1. The Iraola system (10 kW) in Itsasondo.with 10 members
2. The Lukasain system (65 kW) in Ordizi with 58 members

Plans for 2025 include the development of two additional solar installations: a 100 kW system in Zaldibi and a 60 kW system in Segura. Beyond installations, Hitzar also supports its members with guidance on Tax on Real Estate (OHZ) (Gipuzkoa provincial council, 2025), assisting them in understanding and managing tax obligations related to renewable energy systems.

2.1.3 Characterization of the Hitzar REC´s BM

To characterize the SBMs of RECs, the traditional Business Model Canvas (BMC) (Osterwalder and Pigneur, 2009) was adapted, resulting in an extended version that we have called the Sustainable Business Model Canvas for RECs (SBMC-REC) (Bocken et al., 2014; Osterwalder, Pigneur & Tucci, 2005) and integrates sustainability dimensions such as the governance model and the triple bottom line impacts, aligning with SDGs (United Nations, 2025). It has been shaped by complementary perspectives from Hall & Roelich, (2016); Hannon et al. (2013) and Richter, (2013), providing a robust tool to analyze and compare innovative approaches in the energy sector.

TABLE 1 SUSTAINABLE BUSINESS MODEL CANVAS FOR RECS (SBMC-REC) ACRONYMS: SDG: SUSTAINABLE DEVELOPMENT GOALS

Block	Information	Source
Value proposition	Need/problem addressed	(Boons and Lüdeke-Freund, 2013; Engelken *et al.*, 2016)
	Offer (good and/or service)	
	Organisations' meaning of existence	
Value delivery	Customer segment	(Boons and Lüdeke-Freund, 2013)
	Key channels (promotion and distribution)	
	Key relationships	
Value creation / Supply chain	Key resources (technological, human capital, knowledge)	(Pereira and Caetano, 2015)
	Key activities	
	Key partnerships	
Value capture	Financial model (how the model is financed)	(Osterwalder *et al.*, 2005; Pereira and Caetano, 2015)
	Cost structure (capital and operational costs)	
	Revenue streams (how earnings are obtained)	
Governance	Promoter (who initiated the project)	(Hellström *et al.*, 2015; Smith, 2007; Zott and Amit, 2010)
	Focal firm (who runs the business)	
	Governance model (how is the business managed, how is ownership defined, how are responsibilities shared, how are agreements and decisions made)	
	Legal form (SL, S. Coop, etc.)	
Triple bottom line impacts (sustainability)	Social (+/-): Positive or negative impact on local, regional society, lifestyles	(Ibarra *et al.*, 2023)
	Economic (+/-): Local, regional economic development	
	Environmental (+/-): Positive or negative impact on natural environment	
	SDG (+/-): Positive or negative impact on what sustainable development goal)	

While the block labeled “Value Creation” refers to the configuration of key resources, activities, and partnerships that enable value delivery, the broader effects of the business model on stakeholders are captured in the Triple Bottom Line section. This block represents the sustainable value generated across social, environmental, and economic dimensions, in alignment with the SDGs. Following recent literature (Lüdeke-Freund *et al.*, 2024), value creation for sustainability is considered to encompass the processes of maintaining, unlocking, and sharing value with diverse stakeholder groups

An example of how sustainability principles shape business models can be seen in the solar business model (BM) described by Bankel & Mignon (2022). In this model key roles such as property owner, PV system owner, and electricity consumer can be assigned to different actors depending on the project configuration. Core activities include project development, technology purchasing, installation, monitoring, and maintenance, with applications ranging from residential to utility-scale setups. These principles are reflected in Hitzar’s approach, where roles and activities are tailored to meet the needs of its energy community.

Hitzar’s model, has been structured around the SBMC-REC (Table 2). The SBMC-REC for Hitzar was completed through interviews with members of the energy community, providing first-hand insights into the roles, key activities, and relationships that define the model.

TABLE 2 SBMC-REC OF HITZAR REC ACRONYMS: GHG: GREENHOUSE GAS; SDG: SUSTAINABLE DEVELOPMENT GOALS

Value proposition	**Need/problem addressed**	• Contribute to the energy transition in the Goierri region. • Provide members with advice on property tax (IBI).
	Offer	• 2 solar installations in private roof 1.The Iraola system (10 kW) in Itsasondo.10 members • 2.The Lukasain system (65 kW). In Ordizi. 58 members
	Organisations' meaning of existence	• “We are a cooperative, a non-profit association.” • Ensuring transparency and compliance with the law in our activities is essential.
Value creation	Key partnerships	• Ernamuina: Seed funding or incubation -Biziola.coop: Biziola Cooperative • Goieki (Goierriko garapen agentzia): Goierri Development Agency • Nafarkoop: Nafarkoop Cooperative -Farapi: Farapi • Goiener (initially) • Ekisolar (solar energy company) • Ingeteam (engineering and energy company)
	Key activities	• Generate renewable energy • Supply members with renewable energy • Explore local opportunities • Understand local regulations • Project development 1) Select a suitable roof 2) Conduct a preliminary assessment 3: Develop a feasibility project and explore financing options 4: Obtain permission from Iberdrola for the desired KW installation 5: Proceed with the installation process

	Key resources	• Human Resources: Skilled personnel for installation, maintenance, and community outreach; legal and technical consultants. • Technological Resources: Advanced solar panels, inverters, and energy monitoring systems. • Financial Resources: Membership contributions, grants, and subsidies. • Social Resources: Strong member network and partnerships with local organizations for community engagement.
Value delivery	**Key relationships**	• Member Engagement:. • Local Partnerships:. • Community Trust:
	Key channels	• Website: Comprehensive information on the community, projects, and how to join. • Email Support: A dedicated email for inquiries and assistance. • Consultation Services: Personalized advice on membership, renewable energy systems, and property tax (IBI). • Energy Delivery: Direct supply of renewable energy to members via the local grid. Allocation of energy packages (1 kW or 0.5 kW) tailored to member needs. Surplus energy management and compensation through grid connections. • Community Outreach: Local events and forums to foster engagement and attract new members.
	Customer segment	Members in the Goierri region (Itsasondo, Ordizi, Legorreta, Zaldibi) and future members
Value capture	**Cost structure**	• Capital costs for installation (solar panels, infrastructure). • Operational costs for maintenance and monitoring. • Administrative costs for cooperative management and legal compliance. • Community engagement and educational initiatives. • Profits are reinvested in the community to increase capacity.
	Financial model	• Membership fees (€20/year). • Additional fees for energy consumption from installations (€30/year). • Grants and subsidies for renewable energy projects.
	Revenue streams:	• Membership contributions. • Revenue from surplus energy sold back to the grid. • Local or regional funding initiatives supporting renewable energy.
Governance	**Promoter**	Initiated by local residents of Itsasondo with early support from Goiener.
	Focal firm	Managed and operated by Hitzar Koop., the cooperative itself.
	Governance model	Democratic decision-making within the cooperative, with members actively participating in key decisions and project developments.
	Legal form	Cooperative (S. Coop.)
Sustainability	**Social**	Strengthens community cohesion, reduces energy poverty, and empowers members through participatory decision-making.
	Economic	Provides cost savings for members, reinvests in the community, and supports local economic growth
	Environmental	Reduces carbon emissions, utilizes renewable energy, and minimizes land use impact.
	SDG	Contributes to SDG 7 (Clean Energy), SDG 11 (Sustainable Communities), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action).

The next analysis focuses on a specific value proposition rather than the entirety of Hitzar's business model to provide a more detailed and actionable understanding of one key aspect of its operation. Among the value propositions identified through the SBMC-REC, we chose to examine the delivery of affordable, renewable energy to members. This decision allows for a focused exploration of how this value proposition is realized through one of the cooperative's installations, the 65 kW project in Ordizi. By narrowing the scope to this specific case, we can better understand the practical implementation, challenges, and impacts of this value proposition.

2.2. Qualitative assessment for BM-LCA application

The second step of the methodology consists of three sub-steps that guide the qualitative evaluation of the methodology's applicability: i) understanding the 5 steps of the BM-LCA framework and reviewing reference studies to grasp its practical application, ii) identifying possible applications for the Hitzar REC case study with a focus on its specific value proposition, and iii) analyzing the pros and cons of the application by evaluating factors that facilitate or challenge its implementation.

2.2.1 Understand the methodological approach and its case applications

BM-LCA offers several advantages, including the provision of insights into a broad range of business model elements, as product system, pricing, distribution channels and supply chain (Baumann, 2024), making it useful for business strategy development. By measuring business model environmental performance, it helps companies determine which models to compete with (in terms of sustainability advantage) and supports critical analysis against greenwashing claims. BM-LCA also enables identification of business model elements most in need of environmental innovation and offers a practical way for business and LCA experts to merge their respective knowledge (Goffetti *et al.*, 2022).

TABLE 3 SUMMARY OF EACH PHASE OF THE BM-LCA METHODOLOGY, ALONG WITH A DESCRIPTION OF EACH STEP. ACRONYMS: LCI: LIFE CYCLE INVENTORY; LCIA: LIFE CYCLE IMPACT ASSESSMENT; GHG: GREENHOUSE GAS; BM-LCA: BUSINESS MODEL LIFE CYCLE ASSESSMENT

Phase	**Description** (Böckin *et al.*, 2022)	**Example of jackets** (Goffetti *et al.*, 2022)
Goal and Scope: Descriptive phase	Step 1: Detail the business models and describe them in relation to the product systems using actor analysis. Identify and connect cost and revenue streams for these actors (in and outside the company). This simplifies the identification of relevant economic parameters later. Also state a time period from where to get data.	• Describes rental and sales business models, focusing on roles of suppliers, users, and internal processes. • Maps revenue from jacket sales (5,000 SEK) and rental fees (600 SEK) while tracking costs (production, labor, and repair costs). • Collects production cost data (k=2,500 SEK/jacket) and revenue data from customer sales and rentals.
	Step 2: Define system boundaries and the impact categories that will be studied.	• Identifies GHG emissions, resource consumption, and waste as critical impact categories.

Phase	Description (Böckin *et al.*, 2022)	Example of jackets (Goffetti *et al.*, 2022)
Goal and Scope: Coupling phase	Step 3: Define the connection between transactions, (t), and production, q, for each business model. Then determine the Functional Unit as the profit level, π, that will act as target for both business models	• Identifies production costs (2,500 SEK), rental fees (600 SEK), and jacket sales (5,000 SEK) as key inputs • Product lifetime (200 days) as key parameters.
	Step 4: From the actor analysis, identify costs and revenue streams for each business model. Find coupling equations, relationships between q and t so costs and revenues can be expressed with transactions, t. Set up an equation for the Functional Unit (profit), π, as revenues – costs:	• -Profit equation for rentals: $\pi = t_s(30days) - q_s(200\ jackets)$. This links production (q_s) and transactions (t_s) with profit. • -This translates to a physical flow of 200 jackets per month, since, in the linear model, the number of sold jackets equals the required production. • -Functional unit is set as 319,391 SEK profit to allow comparison between rental and sales models.
	Step 5: Solve the equation and find the transactions, tr needed to reach the Functional Unit. From tr, derive the required production, qr. Do this for all business models.	• Calculates required in rental model production (q = 28 jackets) and rental transactions (t = 1,108) to achieve profit target (319,391 SEK). • In sales model (q=200 jackets) (t=200) for same profit
LCI	Construct flow model, the collection of data and the creation of an inventory of environmentally relevant flows scaled to the functional unit	• All flows are normalized to the defined functional unit, which is the monthly profit from jacket sales or rentals (e.g., 319,391 SEK for sales).
LCIA	Translates the LCI data to environmental impact categories using emission factors.	• Quantifies GHG emissions from production and transport as key impact drivers.
Interpretation	Analyze the results from the LCIA and test the calculations sensitivity by conducting a sensitivity analysis. Perform Environmental Hotspot identification.	• Identifies textile production and customer transport as key hotspots for GHG emissions.

The methodology is based on two key principles: shifting the focus from the product to the business and the socio-material perspective in the product chain (Böckin et al., 2022). Case studies applying BM-LCA have covered various business models and product and services typologies (e.g. outdoor clothing designer/retailer; jacket, outdoor lifestyle company; reusable cups, automotive company; battery electric, air purifier (Carolina, 2024; Norin, 2024) demonstrating its applicability across different sectors (Baumann, 2022). However, challenges remain, such as data collection difficulties, especially for new end-of-life technologies and use stage information (Bjørnbet and Vildåsen, 2021). Additionally, BM-LCA has not yet been applied to non-profit business models such as RECs, which may require adaptations to the methodology, further justifying the need for this qualitative analysis of its applicability in this context.

The BM-LCA methodological steps defined by (Böckin *et al.*, 2022) were used as reference (Table 3). To provide a practical perspective and improve understanding, Table 3 also presents a case study on jackets (Goffetti et al., 2022) illustrating how each methodological step can be applied in practice to evaluate the performance of a business model.

2.2.2 Identify possible applications for the case study and analyze their pros and cons.

The BM-LCA study focuses on qualitatively defining how each stage of the process should be carried out, establishing the specific steps required to assess the environmental performance of the most significant value proposition of the Hitzar REC, its second installation in Ordizi of 65kW. This involves understanding the relationship between monetary and material flows and their contribution to environmental, social, and economic sustainability

This application explores practical ways to connect theoretical aspects of the BM-LCA methodology with the real-world dynamics of RECs, a key component of the Hitzar REC as a benchmark for further development. The focus is specifically on the first two phases of the BM-LCA methodology: Goal and Scope: Descriptive Phase and Goal and Scope: Coupling Phase.

In the descriptive phase, the analysis centers on describing the energy system supporting the second installation, which is the primary focus of this study, and establishing the impact categories that will be measured using the BM-LCA methodology. As part of this phase, actor mapping for LCA is also considered, helping to identify where the BM sits within the overall life cycle. This mapping process provides a clearer understanding of the roles and interactions of different stakeholders, facilitating the identification of cost and revenue streams and their linkages to material and energy flows. In the coupling phase, the emphasis is on defining costs and revenues, establishing the functional unit, and formulating the coupling equations. The findings and their implications are further detailed in the Results and Discussion section, where the application of these phases is critically evaluated.

At the same time as possible applications are analyzed, the positive and negative aspects are also evaluated—specifically, the factors that may facilitate this analysis and those that may pose challenges, based on the functioning of the system under review. The results are summarized in Table 4 (Results and Discussion), which highlights the phases of BM-LCA, possible applications to Hitzar's value preposition, and the pros and cons of each step

2.3. Definition of best practices and recommendations

This step uses insights from the analysis to develop best practices and recommendations for RECs. It focuses on strengthening SBMs for RECs, using the BM-LCA as a decision-support tool. While the third stage contributes valuable insights, the main objective of this study is to establish a qualitative foundation for applying the BM-LCA framework to RECs

2.3.1 Application of BM-LCA as decision-support tool for REC

The BM-LCA methodology will be applied as a decision-support tool to guide the strategic and operational development of RECs. This application involves a systematic evaluation of the pros and cons identified in the previous phase to refine and adapt the methodology to the specific context of RECs. To strengthen the qualitative measurement of the BM-LCA approach, we will identify any missing data or overlooked concepts in the deployment of RECs. At the same time, we will explore potential future developments of the methodology, reflecting on how it can evolve to better suit the unique needs of RECs. Additionally, by analyzing the methodology, we can identify its favorable aspects that support the development of REC. These reflections and insights are further explored in the results section (3.3). To enhance the quality and robustness of the impact assessment, we will compare our findings with reference studies and relevant literature that have applied similar analyses.

2.3.2 Development of SBMs for REC

In SBM the value proposition focuses on creating social, environmental, and economic value, aligning the interests of a wider group of stakeholders. It goes beyond just monetary value for customers and shareholders, considering both people and the planet (Geissdoerfer *et al.*, 2018). The SBMC-REC framework encompasses various approaches, including Circular Business Models (CBM), which provide a specific pathway to sustainability by addressing resource efficiency (Mendoza, Gallego-Schmid, *et al.*, 2022).

SBMC-REC and BM-LCA are mutually reinforcing frameworks. BM-LCA quantifies the practical outcomes of SBMC-RECs' theoretical principles, bridging the gap between sustainable intentions and measurable results. For RECs, applying BM-LCA within an SBM-REC framework allows for actionable strategies that align value creation with sustainability goals. Additionally, using the outputs of the methodology, a critical analysis has been conducted, leading to proposals for areas of improvement to make RECs more sustainable business models results section (3.3).

3.Results and Discussion:

This section describes how the BM-LCA methodology is applied to the second installation of the Itsasondo HITZAR energy community (HITZAR.Koop. S., 2024). The first two phases, which are the most relevant for this qualitative analysis of the application of the methodology, are described below. The section concludes with recommendations for REC

3.1. Goal and scope: Descriptive phase

This phase involved three main tasks: (1) clarifying the value proposition of Hitzar REC, (2) describing the energy system of the 65-kW installation, and (3) the impact categories to be measured using the BM-LCA methodology.

In the analyzed business model, the product system (Figure 2) refers to the energy transferred from the PV installation to the users. For this phase, insights from a previous step "Understanding of the REC case study Hitzar" were critical. This analysis provided a detailed understanding of the key actors, their roles, and the flow of resources and information within the system.

The second installation of Hitzar involves a 65 kW solar energy system, distributed in 1 kW or 0.5 kW packages among users (CUPS). The allocation depends on each user's electricity consumption and energy bill. This tailored distribution ensures that the installation aligns with individual energy needs and maximizes efficiency. Once each CUPS has its assigned package (usually 1 kW), Iberdrola (the electricity grid) analyzes how much of that kilowatt is consumed. In the case of surplus energy, it is sold back to the grid obtaining revenue (R2 in fig2). It is important to note that this kilowatt can only be consumed during production hours (when sunlight is available), as there is no battery for energy storage.

Another key aspect of this energy production system is that 10% of the energy produced is allocated to the owner of the roof where the installation is located. In this case, 6.5 kW are designated, which typically are not fully consumed. Therefore, the roof owner earns additional revenue by selling this surplus energy back to the grid (R1 in fig2).

Socio technical product system of SBM-REC: (focus on the 65-kW installation in Ordizi*)*

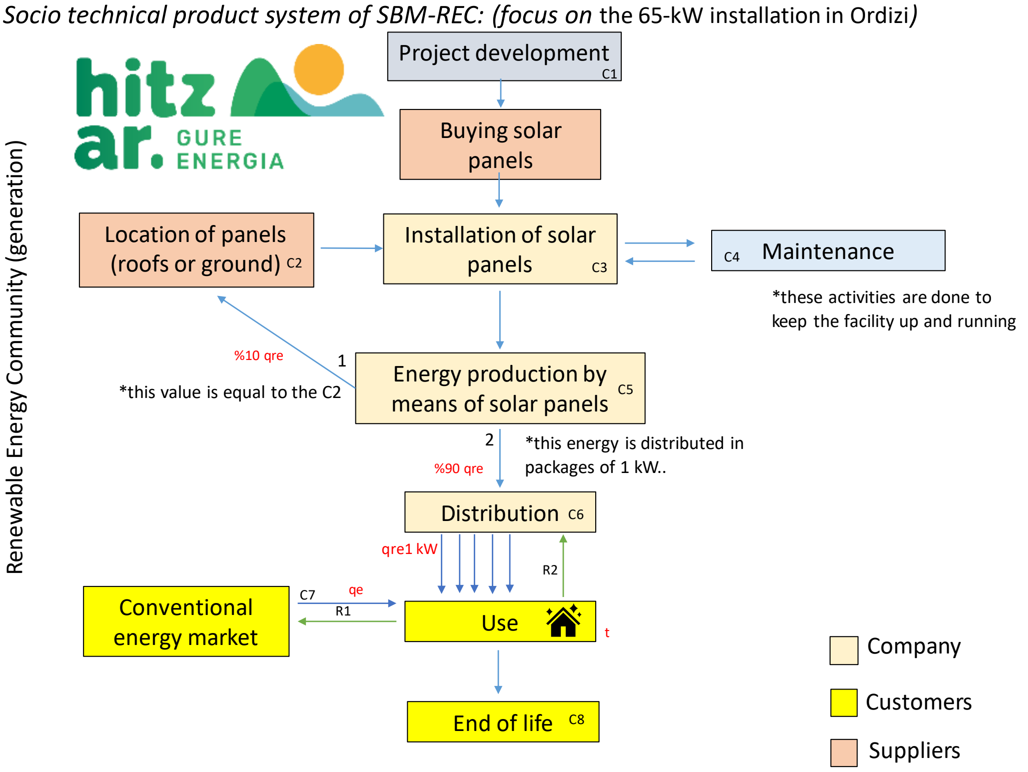

FIG. 2 SOCIO TECHNICAL PRODUCT SYSTEM FOR REC CASE STUDY HITZAR

Regarding the consumption packages, there is a proposal to increase the current limit of 1 kW, aiming to introduce businesses as members of these communities. However, for households, consuming more than 1 kW is generally unnecessary, particularly considering that consumption is limited to daylight hours. Restaurants and shops could also become interesting users, as they may experience peak energy demands during daylight hours. The processes involved in the system are defined in the (Table 4).

TABLE 4 DESCRIPTION OF THE PROCESSES INCLUDED IN THE TECHNICAL SYSTEM OF REC CASE HITZAR

Process	Description
Project development	Define the installation capacity (kW). Verify that the transformer capacity supports the installation. Recruit members for the project, ensuring each member is allocated 1 kW of consumption.
Buying solar panels	Panels are purchased after reviewing and selecting the best available offer.
Location of panels	In the Hitzar REC model, the roof used for the solar installation always belongs to a member of the cooperative. As compensation, the member receives 10% of the energy generated by the system.
Installation	Install the solar panels following technical specifications.

Process	Description
Energy production	Generate energy through the installed solar panels.
Maintenance	Ensure the proper functioning and upkeep of the system.
Distribution	Distributed in 1 kW or 0.5 kW packages among users (CUPS). The allocation depends on each user's electricity consumption and energy bill.

In defining the impact categories for assessment, the most effective approach is to reference EU standards for life cycle analysis (LCA), such as the Product Environmental Footprint (PEF) (Manfredi *et al.*, 2012). However, it is equally important to consider categories relevant to the local context. For example, in regions prone to drought, categories related to water use may be more significant (Lehmann, Bach & Finkbeiner, 2016) (Lehmann, Bach & Finkbeiner, 2016). A recommended strategy involves assessing 25 categories defined by the EF 3.1 (Commission, 2024) method and then applying a weighting system to prioritize those most relevant to the region or REC according to ISO14040-44 (ISO, 2006).

This customization allows the analysis to reflect local environmental priorities effectively. The prioritization process will be guided by input from experts in the field of environmental sustainability and renewable energy, as well as feedback from members of the energy community itself. By consulting these stakeholders, the weighting system can reflect both technical expertise and the community's specific concerns and values.

To simplify decision-making, it is advisable to focus on a few core categories. for REC, these might include climate change (energy-related emissions and savings), mineral depletion (related to the production of energy technologies), and land-use change (centralised vs descentralised energy production systems). While these categories primarily address environmental aspects, economic and social dimensions must also be included. The economic perspective is naturally integrated into the BM-LCA framework (Böckin *et al.*, 2022), but selecting appropriate social indicators remains a significant challenge. This is a critical gap in the methodology, as social indicators must align with the values of RECs. Additionally, it is important that the selected indicators capture potential reflect potential interactions and conflicts between sustainability aspects, such as CO_2 emissions versus biodiversity/land use or CO_2 versus toxicity, depending on the specific context.

3.2 Goal and scope: Coupling phase

The coupling phase is more technical and requires precise data, which can be challenging to obtain. For an initial approximation, this phase focuses on three key elements: (1) Defining costs and revenues; (2) Establishing the functional unit , such as profit margin or energy produced over a specific time period; and (3) Formulating the coupling equations, which link costs, revenues, and energy flows to enable accurate analysis and modeling.

The costs and revenues (Table 5) for the second installation were determined through consultations with project members and technical studies. Fixed revenues (R2) include an annual membership fee of €20 and an additional €30 for consuming 1kw energy from the installation, totaling €50 per member annually. A study conducted by Hitzar estimates total annual cost (C) at approximately €30,000, which can be covered by contributions from around 500 members. This relationship between costs and revenues underscores the scalability of the project, making the community's expansion across the region both feasible and beneficial.

At the same time, the analysis highlights specific costs, based on data from Hitzar's economic plan. Project costs (C1) amount to €5,070, while installation costs (C3) represent €42,980, making them significant components of the total expenditure. Maintenance costs (C4) are €598 annually, and insurance (C5) adds €495 per year. The surface cost (C2) is paid in energy produced by the installation itself, reflecting an alternative payment structure. Other costs, such as distribution (C6) and energy purchased from the grid (C7), are more variable and influenced by external factors, adding complexity to the financial model.

Another interesting debate arises around the sources of data collection, as the choice of sources can significantly influence the results obtained. Depending on the reliability, scope, and precision of the data, the analysis outcomes may vary, highlighting the importance of selecting appropriate and representative data for accurate evaluations. For example, the price paid by the energy supplier for surplus energy (R1) can vary between the highest rate of 0,078€/KW (*Goiener*) and the lowest 0,04 €/KW (*Factor energia*). This variability underscores the importance of conducting a sensitivity analysis, as it allows for assessing the impact of fluctuating data inputs on the final results.

TABLE 5 COST AND REVENUES OF THE SOCIO TECHNICAL PRODUCT SYSTEM

C	Cost	R	Revenue
C1	Cost of the project	R1	Revenue of selling the energy
C2	Cost of surface	R2	Revenue of member contributions
C3	Cost of installation	**Product (energy) flow**	
C4	Cost of maintenance		
C5	Cost of insurance	q re	renewable energy produced
C6	Cost of distribution	q e	grid energy consume
C7	Cost of energy	t	Use period
C8	EoL cost	k	Cost per unit (external data)

Additionally, based on economic plans from the community, it becomes evident that other expenses could also be integrated into the analysis, such as internal management, communication, administrative services, and project pre-evaluation. However, it is important to focus the results on costs and revenues directly related to the value proposition to maintain clarity and relevance in the analysis.

To define the functional unit, various indicators can be used, including profit margin and rate of return (Schmidlin, 2014), which is particularly interesting for our non-profit business model. This opens the possibility of tailoring the functional unit to better align with the objectives of non-profit organizations, where the focus is not solely on profit but also on social and environmental impact. The profit can be the amount of money that is needed to survive, or the money that will be needed to develop improvements in the infrastructure. The functional unit can be the revenues of the energy consumption system minus all associated costs over a one-year period.

Finally, the coupling equations will link the quantity of energy produced or consumed with the corresponding unit price of energy. This approach allows us to assign specific values to the cost categories. For the cost calculation, we will use the unit price of energy purchased from the grid, reflecting the external energy supply costs. Similarly, to define the revenue categories, we will use the unit price offered by energy suppliers for the surplus clean energy generated by our installation but not consumed locally.

A key point of debate here is that these external prices, both for grid energy and for the surplus energy we sell, are beyond our control and are often highly variable. This volatility introduces significant uncertainty into the financial calculations, complicating the accurate assessment of both costs and revenues. In this context, sensitivity analysis can be particularly useful in identifying the range within which the business model remains viable and determining which parameters may need adjustment to ensure financial stability.

Table 6 provides a concise overview of the key results from applying the BM-LCA methodology in REC. It highlights the main phases, possible applications, and key pros and cons for each step. To better understand the costs and flows referenced in the table, it is essential to see the sociotechnical system diagram (Figure 2), which provides a visual representation of the processes and interactions within the system, and the cost and revenues categories (Table 5). The logic used by Goffetti (Table 3) for the business model of jackets differs significantly from what can be assumed within the context of an energy community installation.

TABLE 6 BM-LCA IN REC. ACRONYMS: LCI: LIFE CYCLE INVENTORY; LCIA: LIFE CYCLE IMPACT ASSESSMENT; GHG: GREENHOUSE GAS; BM-LCA: BUSINESS MODEL LIFE CYCLE ASSESSMENT

BM-LCA		**BM-LCA in Hitzar REC, the 65-kW installation in Ordizi**	
Phase	**The theory**	**Possible application**	**Pros and cons**
Goal and Scope: Descriptive phase	Step 1: (a) Description of the Value preposition (b)Product system (actor mapping + cost/revenue mapping) (c) Data collection	The defined model is based on a project of Hitzar REC value preposition and reflects the necessary steps for 65-kW installation in Ordizi	Some stages, such as maintenance, end-of-life processes, and the installation of solar panels, lack clarity in terms of detailed information.
	Step 2: (a) Impact categories for the environmental assessment	For indicator selection, EF impact categories used in ISO14044, and the EF impact category indicator used in the 14044:2006, focusing on variables relevant to energy communities.	Selecting indicators that reflect social aspects remains challenging since existing standards prioritize environmental metrics. Tailored indicators can bridge this gap to some extent.
Goal and Scope: Coupling phase	Step 3: (a) Cost and revenue categories (b) Values of cost prices and parameters	Costs and revenues were defined based on observed interactions within the system for Hitzar's second installation.	Energy costs (C7) are highly volatile, and the price offered by suppliers for renewable energy (R1) remains low, complicating financial predictability. Using the profit margin as an indicator could help address this uncertainty by providing a clearer picture of financial stability.
	Step 4: (a) Coupling equations (b) Functional units	Relate energy quantities (qre, qe) to costs or revenues at a given price "k" based on real-time energy prices.	Energy generation (qre) occurs only during daylight hours, leading to variations in the equations by time of day. Grid energy prices (C7) also fluctuate.
	Step 5: (a) Calculate the cost and revenues	To calculate the most critical costs and revenues (C6 and R1), data on energy consumption and renewable generation (qre) per user are required.	Completing these calculations is difficult without a full annual dataset (t) for meaningful consumption and generation patterns.
LCI	Identify material flows (e.g., raw materials, emissions) and scale to the functional unit	Renewable energy flows, grid energy flows, payments for energy, and revenues from surplus energy sales are included in the inventory.	These inventories will vary daily. Averages or seasonal groupings may offer more actionable insights. The distances involved in production and consumption

BM-LCA Phase	The theory	BM-LCA in Hitzar REC, the 65-kW installation in Ordizi Possible application	Pros and cons
			can also be important when defining the inventory.
LCIA	Use emission factors to convert LCI flows into environmental impacts	This phase can be debated as it requires measuring appropriate values. What metrics truly characterize REC? Social-oriented indicators, as mentioned by Bocken and others, and references to the SDGs in the 2030 Agenda could be used.	Considering the social, environmental, and economic sustainability potential of these business models, reflecting impacts across all three categories is vital. However, it is highly challenging to adapt the methodology to include such a comprehensive set of indicators.
Sensitive analysis	Analyze environmental hotspots and test sensitivity of results (e.g., see which factors most affect impact).	Given Hitzar's plans to develop more installations by 2025, this analysis could inform improvements for future projects.	Imagining future scenarios (e.g., battery storage or increased production capacity) is challenging due to external influencing factors, such as market volatility and policy changes.

A key divergence is the temporal variability of energy production in RECs, which depends on daylight hours, requiring adaptations to reflect its impact on financial and material flows. Additionally, while the original framework emphasizes environmental and economic factors, RECs necessitate tailored social impact indicators, such as community engagement and equity. Cost and revenue categories in RECs are also more dynamic, influenced by fluctuating energy prices and the absence of traditional end-of-life processes. Adapting the BM-LCA methodology to include metrics for intermittent energy production and social sustainability could make it more effective for evaluating RECs.

3.3 Definition of best practices and recommendations for the case REC

Applying the BM-LCA methodology to RECs requires balancing their social mission with technical, economic and environmental considerations. While these communities often emphasize social values, it is crucial to integrate technical and financial aspects into their operations in order to become a SBM. At the same time, environmental aspects must not be overlooked, ensuring that social and economic progress does not come at the expense of the enviroment. Furthermore, the participation of diverse stakeholders is vital, as their roles and contributions directly influence the sustainability and scalability of these initiatives. A comprehensive approach addressing these dimensions is essential to maximize the impact and long-term viability of REC.

To effectively use BM-LCA as a tool in the development of RECs, it is essential to address both the strengths and challenges identified during its application. One key challenge is that the data requirements of BM-LCA reveal gaps in the comprehensive understanding of current business models. While business models are often analyzed in fragmented ways, the process of collecting all necessary data highlights the full complexity of cost and revenue structures. First, efforts should be made to improve data collection practices to reduce variability and enhance the accuracy of results. Rather than strict standardization, gaining more experience with BM-LCA and developing guided protocols could provide a more practical approach at this stage.

Additionally, integrating tailored indicators that reflect local priorities, such as water usage in drought-prone regions or social indicators that evaluate community impact, is crucial. The volatility of energy prices and associated costs can complicate financial calculations, so conducting sensitivity analyses and developing future scenarios, including policy changes and technological advancements like battery storage, is recommended. Finally, to maximize the impact of BM-LCA, priority should be given to creating scalable and replicable models that adapt to different contexts, strengthening the role of RECs in the sustainable energy transition.

Even though BM-LCA was not fully applied, its partial use already provided valuable insights into cost structures, revenue streams, and sustainability trade-offs, highlighting its potential as a decision-support tool. Using the outputs of the methodology, a critical analysis has identified areas for improvement to make RECs more sustainable. Key recommendations include simplifying system operations, minimizing the impact of energy price volatility, and refining governance to enhance transparency and participation. These steps aim to improve scalability, adaptability, and resilience in the face of market and operational challenges. Scalability remains a key challenge for RECs, as noted by Mendoza & Ibarra, (2023)who emphasize the role of adaptive strategies to ensure economic and operational viability across diverse contexts.

4.Conclusions

This paper qualitatively analyzed how BM-LCA can be applied in practice to evaluate and improve the sustainability performance of REC's business models, using Hitzar REC as a case study, while identifying methodological challenges and opportunities for further improvement in assessing complex systems. The study demonstrates that BM-LCA is a powerful tool for aligning sustainability objectives with economic feasibility in RECs. The analysis of Hitzar's 65-kW installation highlighted the importance of focusing on a well-defined value proposition, which serves as the foundation for targeted and actionable insights. By integrating material and monetary flows, BM-LCA provides a comprehensive assessment of the environmental, social, and economic impacts of RECs, helping them achieve sustainable business model transformations.

The traditional BMC (Osterwalder and Pigneur, 2009) was adapted, resulting in an extended version that we have called the SBMC-REC, the integration of this SBMC-REC into the "Goal and Scope" phase of BM-LCA represents methodological advancement. This SBMC is specifically tailored to include sustainability dimensions such as governance and triple bottom line impacts. While this framework has not yet been formally applied or integrated into the BM-LCA methodology, we propose its integration into the first phase, "Goal and Scope: Descriptive Phase," specifically in Step 1, where the business model is defined. By incorporating this framework at this stage, we can enhance the characterization of the business model, ensuring a more comprehensive analysis of its cost and revenue structures, sustainability aspects, and overall impact. This qualitative addition enhances the clarity and structure of the analysis. This explicit connection between the conceptual SBMC-REC and the practical BM-LCA framework represents a key strength of the approach and a valuable contribution for aligning business model design with sustainability assessment. The feedback loop between the SBMC-REC and BM-LCA is particularly valuable, as the outcomes from the BM-LCA process inform adjustments to the SBMC-REC, resulting in improved design and functionality of the business model. This dynamic interplay ensures that both frameworks evolve to better address the specific needs and challenges of RECs.

In the future, the present research will continue expanding the application of BM-LCA to explore and compare different scenarios within RECs. This includes integrating battery storage systems, hybrid energy generation methods (e.g., combining solar and wind), to evaluate their impacts on sustainability and economic performance. Quantitative refinements, supported by the development of sector-specific databases, will enable consistent comparisons across different REC models, Mendoza and Pigosso (2023) highlights that advancing CE strategies requires robust data collection, stakeholder collaboration, and systemic approaches. Additionally, a cradle-to-grave approach will be adopted to assess the lifecycle impacts of infrastructure components, such as solar panels and batteries. Comparative studies with other RECs within the analysed region in Spain, will provide valuable benchmarks and insights into best practices.

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