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Sustainable Energy Provision at the Bottom of the Pyramid: Blueprint for Early Repurposing Business Models Using Second-Life Batteries

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ABSTRACT

This study presents a blueprint for an early-stage business model focused on repurposing second-life electric vehicle (EV) batteries for solar-energy storage in Bottom of the Pyramid (BoP) markets. Addressing the critical need for affordable and sustainable energy solutions there, the research integrates principles of strategic and innovation management, international management at the BoP, and management for the circular economy. The proposed framework of an early repurposing business model highlights four key design themes: novelty, efficiency, complementarity, and lock-in, tailored to the unique challenges and opportunities in these markets. A case study on two remote villages in the Brazilian Amazon deepens our blueprint for an early repurposing business model at the BoP.

1 | Introduction

The Bottom of the Pyramid (BoP) still remains a largely unexplored market with significant potential for innovation and impact. Representing over four billion people worldwide (Méndez-León et al. 2024), the BoP comprises of low-income communities where many consumers have limited access to resources, infrastructure, and services, such as affordable and reliable energy (Dentchev et al. 2022; Prahalad and Hart 1999). Despite this, business models targeting BoP markets often fail to address their unique challenges, including low purchasing power, inefficient markets, and environmental vulnerabilities (Dentchev et al. 2022; Oskam et al. 2021). Consequently, there is a growing demand for innovative business models that balance economic, social, and ecological objectives to drive sustainable development in these regions (Lüdeke-Freund et al. 2022).

However, BoP research has primarily focused on economic and social sustainability, largely ignoring environmental sustainability (Ben Letaifa and Reynoso 2015; Du et al. 2021), even though the BoP is disproportionately affected by environmental issues such as global warming (Pongeluppe 2022). Thus, there is a crucial need to also address ecological sustainability at the BoP (Dentchev et al. 2022), especially in light of global obligations for sustainable resource use and material cycle closure in a circular economy (Mayer et al. 2019).

In particular, energy access represents a critical challenge for BoP markets, particularly in remote areas where the reliance on diesel generators persists. These generators are not only costly to operate but also exacerbate environmental degradation, contributing significantly to greenhouse gas emissions (Trindade et al. 2022). The use of renewable energy sources like wind and

This paper explores business models for the Bottom of the Pyramid (BoP), emphasizing ecological sustainability and economic viability. It proposes using circular economy principles, such as reuse and recycling, demonstrated through a case study on reusing car batteries for solar storage. The study highlights benefits and stresses the importance of economic viability for scaling.

sun fails because batteries for storing volatile energies are too expensive for the BoP (Thakur et al. 2022). Therefore, sustainable and cost-effective solutions are urgently needed in these areas (Icaza-Alvarez et al. 2023). One promising approach involves leveraging the principles of the circular economy (Bocken et al. 2014) through repurposing (Geissdoerfer et al. 2017) affordable used electric vehicle (EV) batteries for solar energy storage in a second life. By extending the lifecycle of these batteries, businesses can create economical and environmentally conscious energy solutions tailored to the BoP (Jeppe et al. 2023; Jiao and Evans 2018).

To the best of our knowledge, there is currently no blueprint for repurposing business models at the BoP, hence, the aim of this study is to first document the current state of research on early repurposing business models at the BoP in order to develop a framework in emerging industries (McDonald and Eisenhardt 2020) that evolves from conceptual ideas to more detailed models through reflection and learning in the case study (Snihur et al. 2021; Teece 2010). Therefore, the following are two research questions that need to be addressed:

1. What is the consolidated current state of knowledge on early repurposing business models for the BoP? and
2. How can this be further developed through a case study?

Drawing on insights from strategy and innovation management, BoP-specific research, and circular economy principles, the development of the blueprint integrates four interrelated design themes—novelty, efficiency, complementarity, and bonding—that address the unique constraints and opportunities of BoP markets to create and capture value (based on Amit and Zott 2015).

While the technical feasibility as well as social and ecological benefits of this solution are evident (Strickland et al. 2014; Trindade et al. 2022), its business model requires assessment to drive necessary adoption (Korjani et al. 2021). Such assessments are crucial for scaling ecologically and socially beneficial initiatives (Amit and Zott 2015) by mobilizing sufficient private capital (Kahn et al. 2023).

Using the community of Nova Esperança in the remote Amazon as a case study example for remote communities worldwide, this research develops a blueprint for an early repurposing business model, using repurposed batteries for solar energy storage and therefore sustainable energy provision. The findings provide actionable insights for practitioners and policymakers and theory-building findings for researchers, offering a replicable framework for scaling sustainable energy innovations in similar contexts.

This also determines the course of the study: The current state of knowledge of an early repurposing business model for the BoP is consolidated, and the research gap is concretized through a critical review of the literature on early business models, first in general, then specifically at the BoP, and finally in relation to repurposing. Additional insights will be gained using the case study, which will contribute to the reduction of the research gap. The study background and methodology, the results, and the implications are presented before the article concludes with limitations and an outlook. By addressing the dual imperatives of ecological sustainability and economic feasibility, this study contributes to the broader discourse on inclusive business models and sustainable development.

2 | Critical Literature Review

Designing early repurposing business models for second- or multi-life applications at the BoP encompasses three key research domains: Early business model design in Strategic and Innovation Management (2.1), Management at the BoP in International Management (2.2), and Repurposing for second- or multi-life applications in Management for the Circular Economy (2.3), which are to be consolidated into a framework for the blueprint for early repurposing business models at the BoP (2.4).

2.1 | Early Business Models

The concept of a business model lacks a universal definition in academic literature (McDonald and Eisenhardt 2020). It is broadly understood as "the essential value creation and capture activities of a business enterprise in a condensed and abstract form" (Aversa et al. 2015, 151). Interpretations vary based on perspectives such as real companies, cognitive/linguistic schemas, or formal conceptual representations of organizational operations (Massa et al. 2017; Shepherd et al. 2023), research domains like e-business, strategy, or innovation (Zott et al. 2011), and whether viewed as a dynamic process or static content (de Wit and Meyer 2010). Business model understanding also changes with their maturity level: from early design ("crafting," Amit and Zott 2015), minimal viable models (Amit and Zott 2021; Zott and Amit 2024), to detailed designs in nascent markets (Cusumano et al. 2019; McDonald and Eisenhardt 2020). This article views business models as formal conceptual representations of organizational operations, focusing on the static outcome of the early design phase, especially for circular economy models in emerging economies.

The design process is often based on the dynamic capability framework (Amit and Zott 2015; Teece 2007), involving collective sensing, seizing, and reallocating capabilities (Pitelis 2022; Pitelis and Teece 2018). Early design is a "trial and error" approach (McDonald and Eisenhardt 2020), rooted in the dynamic capability of "sensing" (Teece 2007). It starts with exploring vague ideas on value creation, using methods like "adjacent play, borrow from peers," and "hands-on learning" (ibid.). After reflection and learning, an early business model forms, later evolving into a detailed model including value proposition, value architecture, and profit model (Blank 2013; Foss and Saebi 2017).

In content, early design should focus on value creation and capture (Oskam et al. 2021) that drive business models' implementation speed. Economic value creation sources derive from the theory of economic rents (Brandenburger and Stuart 1996) and are explained as the difference between customers' willingness to pay and suppliers' opportunity costs. Willingness to pay is

the maximum price a buyer will pay (Hanemann 1991), while supplier opportunity costs are the forgone benefits of the next best resource use (Bowman and Ambrosini 2000). Value capture is the portion of generated value a company retains (Dyer et al. 2018). Negotiations determine value shares, with the customer's share being the difference between willingness to pay and selling price, the company's share between selling price and purchase price, and the supplier's share being the difference between purchase price and opportunity costs (Brandenburger and Stuart 1996).

According to Amit and Zott (2015, 322), the sources of a company's value creation and capture are influenced by four "antecedents" of early business model design (also called "design driver," ibid. 2021, 147), which they identify from cases on nine start-ups: goals (of creating and capturing value), templates (of incumbents and others), environmental constraints (i.e., constraints in the corporate environment), and stakeholder activities (see Figure 1), i.e., a consideration of the company (goals) and the environment.

Seizing, as the second dynamic capability in the early business model design phase concerning content, should focus on four distinct business model "design themes" (Amit and Zott 2015, 2021) that resemble competitive advantages, also depicted in Figure 1:

1. A lock-in-oriented business model design focuses on elements facilitating stakeholder attraction and retention, such as standardization advantages.
2. An efficiency-oriented business model design aims to minimize costs or differentiate activities in a cost-efficient manner.
3. A novelty-oriented business model design centers on "the adoption of new activities, new ways of linking activities, or new ways of governing activities" (Amit and Zott 2015, 333).
4. A complementarity-centered business model design emphasizes bundling activities and exchanges to promote synergy effects.

Amit and Zott (2015) also attempt to understand the linkages between antecedents and design themes through interviews with managers of 11 new companies (see also Figure 1). They advocate for balancing value creation for all stakeholders with value capture by the focused company, framing, and benchmarking to achieve efficiency without compromising novelty, leveraging constraints (but also opportunities) in the corporate environment for inspiration, and enhancing complementarities by orchestrating new networks (i.e., ecosystems in the sense of Adner 2017).

2.2 | Early Business Models at the BoP

Emerging markets, classified in 2022 as countries with a gross domestic product (GDP) per capita ranging from 1046 to 4095 US dollars (USD), constitute the majority of the world's population, and many of them are recognized as economically promising growth markets (Ghauri et al. 2021; Pels and Sheth 2017; World Bank 2022). Consequently, their significance in the global economy is escalating (Le et al. 2023; Pels and Sheth 2017). While management and business model design predominantly stem from traditional economies, their direct application to emerging markets proves challenging (Landau et al. 2016).

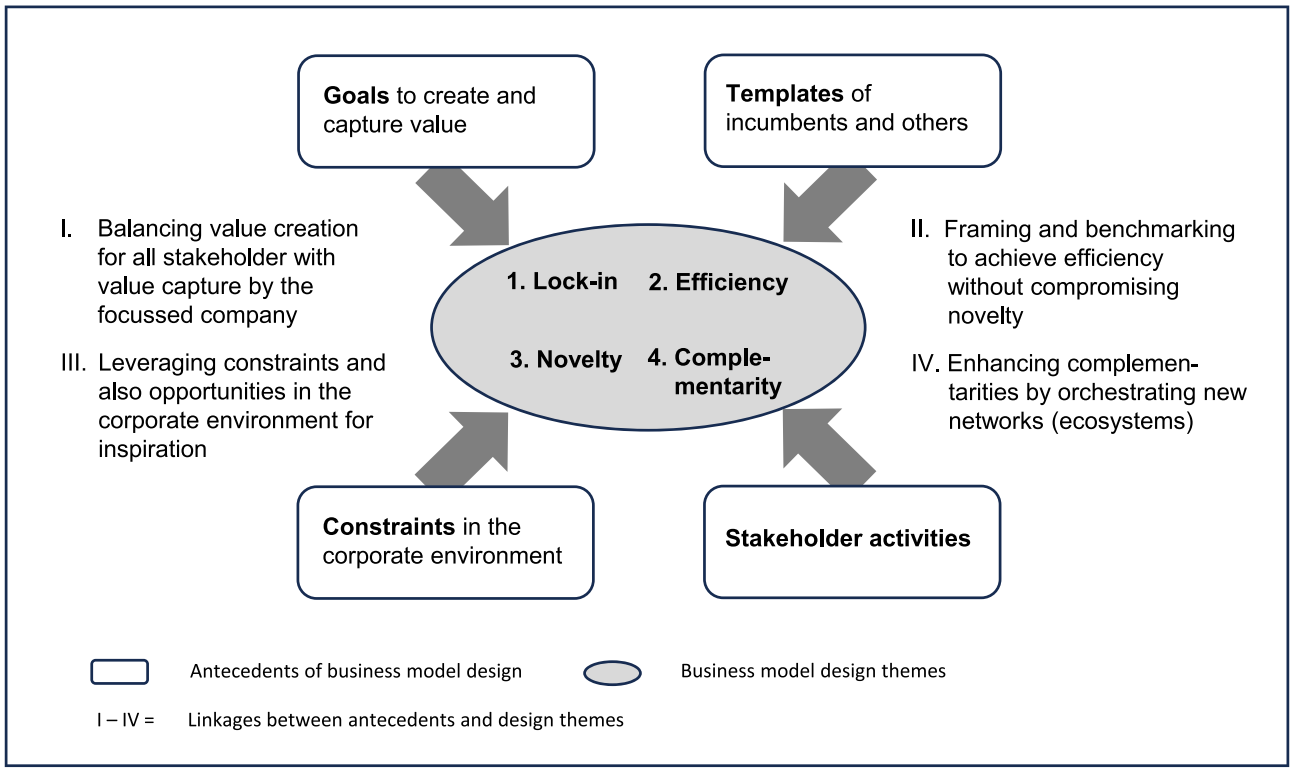

FIGURE 1 | Early business model (own extension of Amit and Zott 2015, 334).

The constraints of international management are heightened in emerging markets, particularly at the base of the pyramid (BoP), given low consumer incomes and inefficient markets (Ciambotti and Pedrini 2021; Dentchev et al. 2022; Klarin and Suseno 2023; Le et al. 2023). The limited purchasing power among the poorest groups restricts value creation and consumption, potentially rendering business models unviable (Lashitew et al. 2022). Moreover, operational costs are increased due to market inefficiencies, necessitating product modifications (Matta et al. 2008; Ries 2011). Welfare burdens through taxes further exacerbate these challenges, threatening economic viability (Lashitew et al. 2022).

Despite these hurdles, opportunities for value creation at the BoP exist, driven by low factor costs and the aggregated purchasing power of consumers (Rietveld and Patel 2024). Innovative solutions that cater to the needs of low-income consumers and address societal challenges can mitigate negative externalities, fostering sustainable business models (Hart and Sharma 2004). Navigating the complexities of emerging markets and the BoP requires collaboration with diverse stakeholders, including governments and non-market actors (Hart and Sharma 2004). In the early phases of business model design, the dynamic capability of "sensing" must consider these constraints and opportunities (Pitelis 2022; Pitelis and Teece 2018). These constraints influence sources of value creation directly and indirectly by affecting other business model antecedents, necessitating goals of socially responsible value creation, and involving new competitors and stakeholders.

Operating in emerging markets at the BoP also impacts the "seizing" phase of early business model design and the development of competitive advantages respectively "design themes" (Amit and Zott 2015; Zott et al. 2011). Historically, top-down approaches aimed to "eradicate poverty through profits" (Hart and Sharma 2004) by focusing on standardization and scalability, thus separating social and economic objectives (BoP 1.0) (Ramani et al. 2023). Subsequent iterations, BoP 2.0 and 3.0, emphasize networks between BoP communities, NGOs, and multinational companies, along with sustainability (Dentchev et al. 2022; Kolk et al. 2014).

2.3 | Early Repurposing Business Models (at the BoP)

Specifically, the principles of the circular economy, which advocate for a shift from linear "take-make-dispose" models to closed-loop systems, are highly relevant at the BoP (Barreiro-Gen and Lozano 2020; Bocken et al. 2014; Brix-Asala et al. 2021). By extending product lifecycles and recovering value from used materials, repurposing contributes to resource efficiency and waste reduction, for example (Geissdoerfer et al. 2017). Moreover, it can foster local economic development and create new opportunities for income generation in marginalized communities (Kirchherr et al. 2017).

Implementing circular economy principles in BoP markets, however, requires careful consideration of local contexts, including infrastructure limitations and informal economies (Lieder and Rashid 2016). Repurposing for new markets offers a way to extend the life of products beyond mere reuse in their original market, which often leads to reduced prices and cannibalization risks (Atasu et al. 2010; Jiao and Evans 2018). However, there is limited systematic examination of business models specifically for repurposing (Hansen and Revellio 2020; de Kwant et al. 2021). Barriers include inadequate incentives for continued use, consumer preference for new products, and lack of value chain transparency (Alcayaga et al. 2019). The primary barrier is the entrenched linear production model, which is increasingly unsustainable due to resource scarcity and environmental cost internalization (Jeppe et al. 2023).

In the early phase of business model design, the "sensing" capability must capture and address specific opportunities and constraints that shape the business environment and influence value creation sources (Amit and Zott 2015; Brandenburger and Stuart 1996). Repurposing can create value through ecological benefits (Amasawa et al. 2020) and cost savings from extended product lifecycles (Jeppe et al. 2023), supported by legislation and government incentives (European Commission 2024).

However, in BoP markets, consumers' willingness to pay more for environmentally friendly solutions is limited. Additionally, repurposing faces challenges like increased product and process complexity (OECD 2019) and finding suitable ecosystem partners (Oskam et al. 2021). Consequently, repurposing business models in BoP markets is still developing. They require support from non-market actors (with influence on economic activities without conducting direct market transactions themselves, such as (local) governments, non-governmental organizations, or local associations). In addition, they require efficient network platforms to thrive (Neesham et al. 2023; Oskam et al. 2021), i.e., ecosystems (Adner 2017). These challenges and opportunities necessitate adjustments in the other "business model design antecedents," such as new competitors and stakeholders for second and third life solutions. Repurposing in BoP markets might also influence the "seizing phase" of the early business model design theme that can complement each other:

1. The "Lock-in" in the existing social context can be strengthened in repurposing models integrated in circular systems to leverage sunk costs especially at the BoP (Lashitew et al. 2022; Ormiston 2023).
2. Addressing market constraints and opportunities through a better cost dispersion with repurposing across various applications over a product's life can increase "efficiency" (Alcayaga et al. 2019; OECD 2019). Products must be designed for multiple lifecycles and be modular to facilitate component changes, standardization, and scalability (Chen et al. 2022; Jiao and Evans 2018).
3. "Novelty" through innovatively adapted approaches can overcome constraints and create opportunities in the BoP business environment through repurposing solutions (Klarin and Suseno 2023).
4. "Complementarity" of partners in inclusive repurposing ecosystems interacting with non-market actors at the BoP can look locally for bottom-up opportunities that are

crucial for realizing repurposing solutions at the BoP, reducing prices through an end-to-end solution with complementary partners (Jeppe et al. 2023; OECD 2019).

2.4 | Consolidation of the Current State of Knowledge Into a Framework for the Blueprint for Early Repurposing Business Models at the BoP

In Figure 2, we can now condense the existing body of knowledge into a framework for an early repurposing business model for the BoP. Numerous studies have previously been conducted on the unique constraints and opportunities at the BoP, as well as repurposing, which not only influence the other antecedents but also (socially responsible) value creation and capture. The effects on the design themes, however, remain relatively unclear. This research gap will be addressed in the remainder of this article.

Thus, in response to the first research question, we have now compiled the consolidated state of knowledge on early repurposing business models for the BoP, as shown in Figure 2. The next step is to address the second research question and to elaborate on this blueprint through a case study on solar-powered storage systems based on second-life batteries in an energy-poor region of Brazil. In doing so, we aim to gain deeper insights into how the design themes must be configured and how they interact at the BoP.

3 | Background of the Study

In order to develop a suitable business model for repurposing in the context of the BoP, the study looks at Brazil, an emerging market with significant income inequality and a considerable proportion of the population living in low-income circumstances (Instituto Brasileiro de Geografia e Estatística 2022). Many rural and remote areas, particularly in the Amazon, face challenges such as limited access to basic infrastructure, energy, and economic opportunities, reflecting the structural characteristics of BoP markets (Trindade et al. 2022).

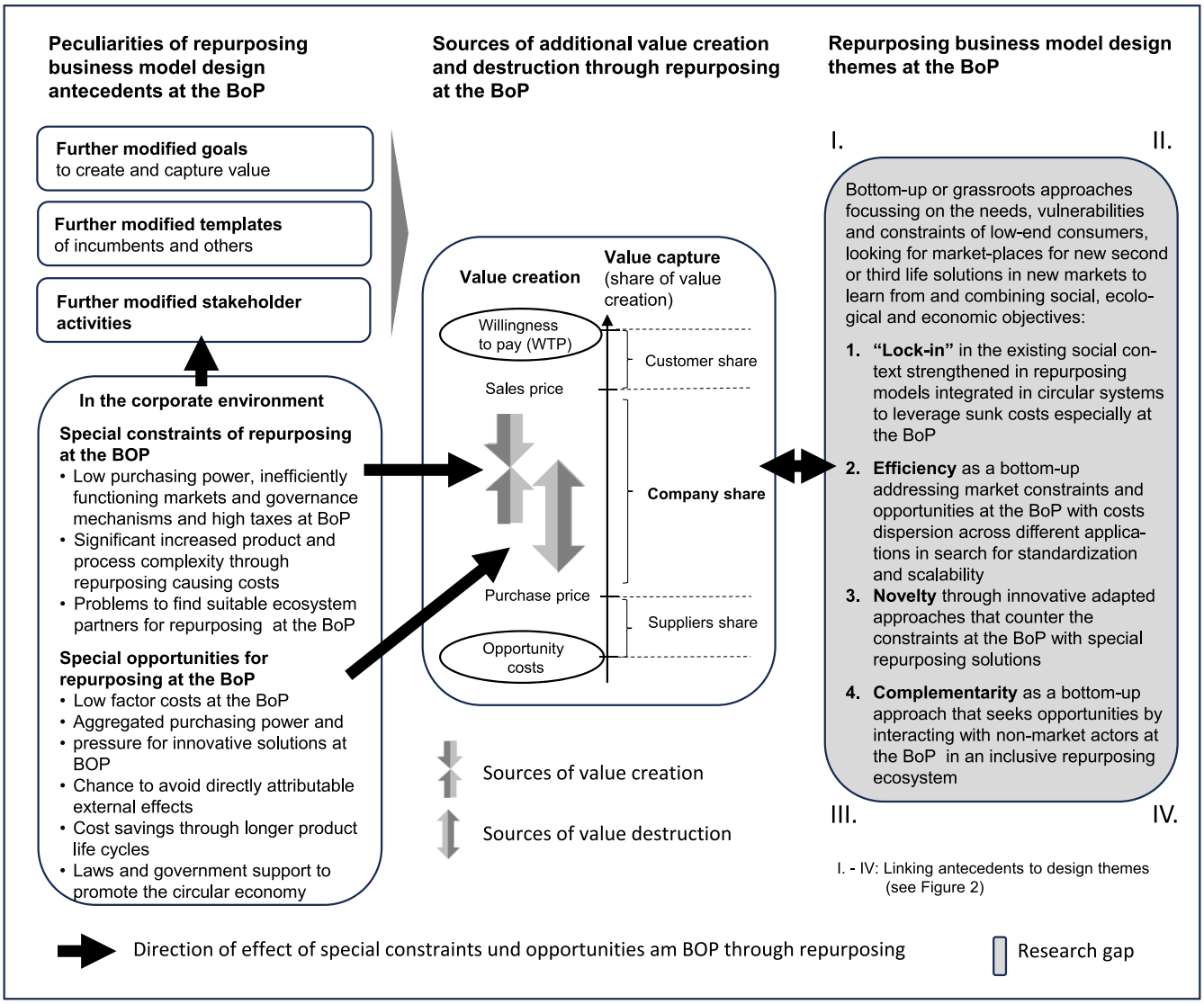

FIGURE 2 | Framework of the current state of knowledge on the blueprint of an early repurposing business model for the BoP (Source: own extension of Figure 1).

At the same time, Brazil holds immense potential for solar energy that offers potentially cost-effective solutions (Icaza-Alvarez et al. 2023), ranking sixth globally in installed solar capacity (Prăvălie et al. 2019). However, high costs of battery storage significantly hinder the utilization of this solar energy (Faessler 2021; Jiao and Evans 2018). Even the granting of state subsidies to make solar systems affordable only led to undersized batteries that limit the effectiveness of solar power, necessitating the continued use of diesel generators (Terkes et al. 2023; Thakur et al. 2022). This created a diesel-solar hybrid system that is neither economically nor environmentally sustainable (Thakur et al. 2022). As a result, many regions in Brazil, especially remote areas like the Amazon, continue to rely on environmentally harmful diesel generators. These not only contribute to high emissions but also incur significant fuel costs (Pongeluppe 2022; Trindade et al. 2022).

For this reason, the repurposing of used EV batteries for storing solar energy is seen as a promising option: It reduces environmental pollution from diesel generators, promotes electromobility, spreads the costs and the emissions from battery production over a longer period (Karadag and Poppo 2023; Reinhardt et al. 2020), and above all, facilitates energy access for marginalized communities, positively impacting health and local productivity (Bichel and Telles 2021). The technical feasibility of repurposing electric car batteries for solar storage in Brazil has been confirmed by the research project 2LifeBat, conducted in 2023 by German and Brazilian universities. Challenging climatic conditions and logistical constraints in the Amazon region were considered.

The Amazon community Nova Esperança was selected for this study after careful consideration of its representativeness. Data from the Brazilian Census and the IBGE (Instituto Brasileiro de Geografia e Estatística 2022) reveal that Nova Esperança's demographic profile, including population size, age distribution, and income levels, closely aligns with the average for rural communities in the Amazon. Furthermore, its energy consumption patterns and high (85%) reliance on diesel generators are typical of many remote villages in the region (García Kerdan et al. 2019). This study serves as a pilot project, with the aim of scaling its findings and applying the lessons learned to other communities facing similar energy challenges, such as those in the Amazon, as well as countries like India or Namibia.

4 | Methodology

In this study, we employ a research design grounded in the principles of qualitative inquiry (Creswell and Poth 2016) with data analysis based on (Braun and Clarke 2006) to further develop the blueprint of a business model that repurposes used car batteries for solar energy storage in remote Amazon communities. Recognizing the multifaceted nature of this issue, the research employed semi-structured interviews with both residents of the target communities and experts. By engaging with diverse perspectives, the study aims to generate rich insights and contribute to a nuanced understanding of the challenges and opportunities associated with this innovative approach to energy access and its business model.

4.1 | Selection of Participants

Participants from two distinct groups were identified: 17 participants from households and village councils in two villages of the community Nova Esperança in the Amazon region to gain first-hand perspectives on the needs and challenges faced by remote communities and 14 experts linked to the German-Brazilian project 2LifeBat, which investigated the feasibility of using used car batteries for energy storage in the Amazon.

Initial contact with villages was established through local NGOs working in the region. Following a series of introductory meetings and discussions with community leaders, structured interviews were conducted on-site in 15 households with community members, representing 80% of the total population across both villages. Households were selected to ensure representation across different socioeconomic data and family structures within the communities. Additionally, two semi-structured interviews were conducted with the village councils of each community. These interviews aimed to gather information on local governance structures, decision-making processes, and community priorities that could influence the feasibility and implementation of a battery repurposing business model.

To gather expert opinions and insights, structured interviews were conducted with 14 academics and professionals from Germany and Brazil with specialized knowledge in relevant fields (see Appendix A for a detailed list of participants and their affiliations). These fields include business administration and engineering (with a focus on electrical engineering and renewable energy systems) and development aid. Participants were identified and recruited through a purposive sampling strategy (Patton 2014), which prioritizes the selection of individuals with rich experience and knowledge relevant to the research topic. Potential participants were identified through a review of relevant literature, online databases, and professional networks. Inclusion criteria were: (a) holding a postgraduate degree (master's, Ph.D., or professorship) in a relevant field; (b) having demonstrable expertise in renewable energy technologies, battery technologies, or sustainable development initiatives in the Amazon region; and (c) a willingness to share their knowledge and insights through a semi-structured interview. Interviews were conducted both in person and online, utilizing video conferencing platforms to facilitate remote participation.

4.2 | Data Collection

The interview structure was based on the framework derived from consolidating the current state of knowledge on a blueprint for early repurposing business models for the BoP, incorporating the four design themes lock-in, efficiency, novelty, and complementarity (see also right side of Figure 2).

The interviews with community members provided valuable insights into local energy needs, priorities, and perceptions regarding the proposed battery repurposing initiative. This aligns with the principles of participatory research and user-centered design, which emphasize the importance of involving end-users in the design and development process (Cornwall and Jewkes 1995). Discussions centered around experiences with

existing energy supply, understanding of repurposed car batteries, community engagement, and ownership.

The interviews with village council members focused on gathering information on local policies and regulations relevant to energy access and environmental protection. Their involvement reflects the importance of understanding and navigating the socio-political context in which the business model will operate (Battilana et al. 2015).

Expert interviews were conducted to gain a comprehensive understanding of the potential for repurposing car batteries for solar energy storage in remote Amazon communities. These interviews focused on the current energy landscape in these communities, the technical feasibility of battery repurposing, and the associated economic and environmental implications. The discussions also delved into critical success factors for a sustainable battery repurposing business model, including market analysis, pricing, and community engagement.

Ethical considerations were central to the design and implementation of the research (Creswell and Creswell 2017). All participants were provided with a detailed information sheet outlining the purpose, procedures, potential benefits, and risks of the study. They were given the opportunity to ask questions and were assured that their participation was voluntary. A written informed consent was obtained from all participants before the commencement of the interviews. To protect the privacy and confidentiality of the participants, all data was anonymized and stored securely. All interviews were conducted in a culturally sensitive manner, with the aid of local interpreters when necessary.

Interviews were audio-recorded with the explicit consent of the participants and transcribed verbatim. The transcription process resulted in over 140 pages of detailed textual data, which formed the basis for the subsequent qualitative analysis.

4.3 | Data Analysis

Concerning the data analysis, the interview transcripts were analyzed using thematic analysis, a widely recognized method in qualitative research for identifying, analyzing, and reporting patterns within textual data (Braun and Clarke 2006; Creswell and Creswell 2017). This approach offers a flexible and iterative framework that allows researchers to inductively derive themes and patterns from the data while also accommodating the use of predefined themes or theoretical frameworks to guide the analysis (Nowell et al. 2017). In this study, a thematic analysis was conducted through a six-phase process, adapted from the frequently cited paper of Braun and Clarke (2006), with the phases (1) familization with the data, (2) generation of start codes and assignment to text segments, (3) grouping themes, (4) reviewing themes, (5) defining and naming themes as well as (6) detailed reporting, see Appendix B. The coding applies to the design themes of early repurposing business models at the BoP, for which 12 subcategories for coding were formed after consolidating the literature on the left-hand side of Figure 2 (see Appendix C). Throughout this process, the research team maintained a reflexive approach, acknowledging their biases and ensuring the analysis was firmly grounded in the data. Regular discussions and peer debriefing sessions further enhanced the rigor and trustworthiness of the findings.

5 | Results of the Study of an Early Repurposing Business Model for the BoP

In this chapter, findings on the design of an early repurposing business model at the BoP are derived from the quotes of the survey participants on the four design themes, i.e., on the four categories and 12 subcategories (Appendix C). They are summarized in Tables 1–4, which detail the research gap shown on the right-hand side of Figure 2.

5.1 | Novelty

Data on incomes in the remote villages of the Amazon suggest that significant changes to existing business models are needed to address the challenging circumstances often encountered initially and "countering constraints at the BoP" (Subcategory 7, see Appendix C). In 2021, the average per capita income in the Amazon region was less than half of Brazil's national per capita GDP (de Oliveira et al. 2022), which, with an average of USD 8918 per capita, was already lower than the global average (around USD 12,688 per capita (World Bank 2024), and "it must be noted that residents don't even have the financial means to finance expensive electrical installations" (Expert 10). This means that even the overall purchasing power in the Amazon region is not favorable and that there are no economic opportunities as a result. In addition, according to community members and experts, the energy markets and government mechanisms there are not very efficient because "there is a tax related to the public illumination. For this they [the villagers] pay the same, but they do not have it. That's an issue." (member of Village Council 1). This corresponds to the complaint of a village resident that "above all, the government regulations do not fit together." Two findings can be derived from this, as a further differentiation of the "countering constraints at the BoP," which indicate that even greater constraints than expected need to be overcome at the BoP (see Table 1):

1. At the BoP, the purchasing power is very low, but contrary to what is emphasized in the literature, even the aggregate purchasing power in the small, decentralized villages at the BoP can be so low that no economic opportunities arise from it.
2. The main constraint at the BoP is not only low purchasing power but also low purchasing power in combination with high transaction costs due to inconsistent government regulations.

The fact that the average per capita income in the Amazon region in 2021 was less than half of Brazil's per capita GDP (de Oliveira et al. 2022) also means that labor cost advantages can only be correlated to a stable energy supply: "Right now, people here earn more money from selling handicrafts than from hunting or fishing. But without reliable electricity, we can't use

TABLE 1 | Results for the design theme "novelty" (own compilation).

Subcategories	Quotes/data	Insights
7. Countering constraints at the BoP	• "... it must be noted that residents do not even have the financial means to finance expensive electrical installations" (Expert 10).	1. At the BoP, the purchasing power is very low, but contrary to what is emphasized in the literature, even the aggregate purchasing power in the small, decentralized villages at the BoP can be so low, that no economic opportunities arise from it.
	• "There is a tax related to the public illumination. For this they [the village people] pay the same, but they do not have it. That's an issue" (member of the Village Council 1).	2. The main constraint at the BoP is not only low purchasing power, but low purchasing power in combination with high transaction costs due to inconsistent government regulations.
	• "Above all, the government regulations do not fit together" (village member).	
8. Taking opportunities at the BoP with special repurposing solutions	• "Right now, people here earn more money from selling handicrafts than from hunting or fishing. But without reliable electricity, we cannot use machines to make these items. We need a reliable power supply with large batteries that can function all day" (member of Village Council 1).	3. The low labor costs at the BoP are hardly relevant given the capital intensity of the solar system with used batteries as storage, so there is no direct substitution of capital for labor. Instead, this cheap solution for energy generation enables an indirect use of the low labor costs at the BoP: The inhabitants of the remote off-grid villages are empowered by energy and light to use their low wages to do craftswork and show initiative.
9. Creating innovative adapted repurposing solutions for the BoP	• "The construction of transmission lines for alternative energy sources such as wind power proves challenging, often due to high costs caused by logistical complexity in view of geographical restrictions. In addition, long term maintenance is expensive" (Expert 1).	4. Novel (innovative) solutions must have a low risk of technical substitution and should reconfigure existing technologies in a new context.
	• "[...] some of these communities will not have enough money to perform maintenance to replace original parts, but if they can get new batteries at low prices, or if they can, for example, extend battery life through proper energy management, those kinds of things, then it could probably be a turning point in the lives of these communities" (Expert 11).	5. The decentralized solutions must be very robust and modular.
	• "The innovative aspect of this initiative lies in its application of established technologies to address a pressing need in a new context" (Expert 8).	
	• "With 12 discarded car batteries (which have fallen below an output of 80%), you can provide a stable power supply to an entire village, like in Nova-Esperança, with 13 households. The system is very robust and less susceptible to faults" (member from Village Council 1).	
	• "from a design perspective for reusability [...], modularity and interface design are perfectly given in a battery" (Expert 4).	

TABLE 2 | Results for the design theme "efficiency" (own compilation).

Subcategories	Quotes/data	Insights
4. Cost dispersion across different applications through repurposing	• "The village people cannot afford new batteries for energy storage" (Experts 1, 9, and 12). • "There have been some initial trials of energy storage with small, old batteries at the Amazon. These attempts were abandoned because the villagers had to pay far too much for batteries, that did not have enough storage capacity" (member from Village Council 1).	1. Second-life respectively repurposing approaches based on a coupling of different sectors open up considerable efficiency potentials beyond cost reduction in only one single sector.
	• "Repurposing is a win-win situation. An approach that fits perfectly into the circular economy system, where the output of one system is used as input for another. They demonstrate this not only through material flows but also through efficient sector coupling" (Expert 1). • "There is a need for a reliable, 24-hour power grid" (Expert 9 and similar other experts and community members).	2. Taking used car batteries for a second life for solar storage might bring the necessary efficiency to new business models at the BoP because it allows a cost dispersion across different repurposing applications.
	• "There is a need for a solution that functions reliably for at least 10 to 15 years, ideally reusing vehicle batteries" (community member and Experts 9 and 12). • "The initially subsidized use of used car batteries for storing solar energy could pay off in the medium term (in less than three years) and, unlike the competing diesel generators, provide free subsidies. The Brazilian government would only have to redistribute the subsidies" (Expert 4). • "If I do not have to scrap the battery after its use in the car but can sell it for a price, perhaps around 60% of the original price, the battery holds a much higher value" (Expert 11).	3. The repurposing solution pays for itself at the BoP after less than 3 years if the subsidies are diverted to diesel and large new batteries.
5. Searching for standardization	• "Standardization plays a pivotal role in ensuring the scalability and replicability of projects like these. By adopting standardized processes for battery collection, sorting, and installation, we would not only streamline operations but also enhance compatibility and efficiency" (Expert 1 and similar Expert 8).	4. The systems should be as standardized as possible to keep complexity costs as low as possible and to enable scaling.
6. Searching for scalability	• "Moreover, standardization fosters innovation by providing a framework for sustainable design and resource utilization. Embracing standardized protocols and interfaces not only facilitates interoperability but also instills confidence among stakeholders, paving the way for widespread adoption and impact" (Expert 1). • "In any case, the more standardized it [a solution] is, the better it can be transferred, and it will not remain a single project because the idea is indeed very exciting and can be applied in many areas of the world since it's [an idea] that is useful everywhere, not just in the Amazon region" (Expert 1). • "There are probably numerous regions and millions of people for whom an additional strong solution using old car batteries could improve their quality of life and energy security" (Expert 6).	

TABLE 3 | Results for the design theme "complementarity" (own compilation).

Subcategories	Quotes/data	Insights
10. Seeking bottom-up in the local context for opportunities	• "Existing structures must be used [...] for collaboration, [...] where batteries are to be refurbished and new facilities developed, installed, maintained, and repaired [...] and the new networks are created primarily through solidarity" (Expert 11). • "Various benefits [for residents of using second-life batteries for solar storage at Nova-Esperança] are there, as well as for the entire country. Not only for residents directly affected by the electricity supply, but also for other residents" (Expert 12). • "... it is not a one time thing .... with the one set of electrification. The energy demand also increases" (Expert 6). • "There are other applications such in ... hospitals, emergency power supply or energy buffering" (Expert 9).	1. At the BoP, the purchasing power is very low, but contrary to what is emphasized in the literature, even the aggregate purchasing power in the small, decentralized villages at the BoP can be so low, that no economic opportunities arise from it. 2. The main constraint at the BoP is not only low purchasing power, but low purchasing power in combination with high transaction costs due to inconsistent government regulations.
11. Interacting with non-market actors at the BoP	• "A close community collaboration with villages, provider of the second life solar system and the installer is important. Here, public-private partnerships can help" (Expert 2). • "... because only through this collaboration we can achieve this overarching benefit that all stakeholders will have" (Expert 1). • "Collaboration with NGO's or international aid organizations would be interesting to ensure scalability" (Expert 2).	3. Interaction with "non-market actors at the BOP" as a public–private partnership is possible.
12. Establishing an inclusive repurposing ecosystem	• "This means we are talking about a network where we have a win-win situation everywhere, thus establishing the foundations of an ecosystem. Therefore, we definitely have positive effects for everyone participating in this network, which is holistic from electricity generation to usage and with participation of all stakeholders in the regions" (Expert 1). • "Furthermore, the Brazilian and the local government could be involved in the ecosystem and, in this process, redirect subsidies for diesel generator and diesel to support the second life battery system during an initial phase as has already been emphasized with the potential analysis" (Expert 2). • "...even customers see their role as stakeholders in ecosystems. The repurpose of batteries presents economic opportunities but requires careful evaluation of costs, logistics, and social equity" (Expert 1). • "Considering that the business models at the BoP are facing inefficient markets, the creation of an ecosystem is very important for the introduction of (affordable) energy storage" (Expert 9). • "Second-life repurposing solutions are of course too complex for only one company to handle" (Expert 13). • "It's crucial, however, that either one company within this network or in the economy as a whole takes control of this (repurposing) process at the BoP perhaps by promoting standards that definitely need to exist for collaboration" (Expert 9).	4. The development of ecosystems is the key to the implementation of novel and efficient solutions and corresponding business models, especially in inefficient markets and even more so in the event of market failure. 5. For novel solutions that also meet the efficiency requirements at the BoP, implementation must be accelerated on the one hand through coordinating individual needs of the consumers (complementarity in consumption) and on the other hand through pooling the strength of providers (complementarity in production) especially in inefficiently functioning or failing markets.

TABLE 4 | Results for the design theme "lock-in" (own compilation).

Subcategories	Quotes/data	Insights
1. Causing sunk costs	• "Consequently, [village people] would heavily rely on this battery system because it's not being built as a temporary solution until power grids are restored, but rather as a permanent solution" (Expert 6). • "For the local people, this would definitely imply a corresponding adjustment or, essentially, a very strong dependency on the functionality of this battery. So, if it works well and reliably, I believe people would rely on it extremely heavily" (Expert 1). • "Any change to the interconnected solution would be expensive" (Expert 2). • "It is also important to [...] establish a leasing model where the batteries are recycled at the end of their [second] life" (Expert 7).	1. The novel yet efficient repurposing business model with complementary users and "production" partners at the BoP creates durable structures with high customer and partner commitment due to long replacement cycles and high sunk costs through leasing contracts.
2. Embedded in the social context at the BoP 3. Integrated in the circular system	• "It is a social progress [...], especially because the social dimension is embedded in the ecological one" (Expert 5).	2. When economically and ecologically sustainable solutions for storing solar energy in used car batteries are embedded in the social development of remote villages on the BoP, this leads to "sunk social costs."

machines to make these items. We need a reliable power supply with large batteries that can function all day" (member of Village Council 1). From this, a further conclusion can be drawn as a special characteristic of "seizing opportunities at the BoP with special repurposing solutions" (Subcategory 8 in Appendix C, see Table 1):

3. The low labor costs at the BoP are hardly relevant given the capital intensity of the solar system with used batteries as storage, so there is no direct substitution of capital for labor. Instead, this cheap solution for energy generation enables an indirect use of the low labor costs at the BoP: The inhabitants of the remote off-grid villages are empowered by energy and light to use their low wages to engage in craftswork and demonstrate initiative.

The high price of diesel for the generators hinders trade and personal initiatives in the off-grid Amazon villages. There is a need for affordable, sustainable energy, but "the construction of transmission lines for alternative energy sources such as wind proves challenging, often due to high costs, logistical complexity, or geographical constraints. In addition, long-term maintenance is expensive" (Expert 11).

All of this results in the need to create "innovative, adapted repurposing solutions for the BoP" (Subcategory 9, see Appendix C), because—according to Expert 11—"[...] some of these communities will not have enough money to do the maintenance and replace the original parts, but if they can get new batteries at low prices, or if they can extend the life of the batteries through proper energy management, for example, then that could probably be a turning point in the lives of these communities." Therefore, the "innovative aspect of this initiative lies in its application of established technologies to meet an urgent need in a new context" (Expert 8 and similarly Expert 11). Above all, decentralized solutions are needed, because "with twelve discarded car batteries (which have fallen below an output of 80%), you can provide a stable power supply to an entire village, like in Nova-Esperança, with 13 households. The system is very robust and less susceptible to faults" (member of Village Council 1). Batteries in particular are a suitable storage solution because "from a design perspective for reusability [...], modularity and interface design are perfectly given in a battery" (Expert 4). The above results lead to two further insights as a specialization of "creating innovative adapted repurposing solutions at the BoP" (Subcategory 9 in Appendix C, see also Table 1):

4. Novel (innovative) solutions must have a low risk of technical substitution and should reconfigure existing technologies in a new context.

5. The decentralized solutions must be very robust and modular.

These five findings demonstrate the need for a novel approach in the business models of circularity with repurposing for a second life at the BoP (summarized in Table 1). Extending Linkage III between the antecedent "constraints in the corporate environment" and the design theme "novelty" in the early business models analyzed so far (Figure 1) by "leveraging constraints and also opportunities in the corporate environment," "novelty" at the BoP is not "nice to have," but much more fundamentally an enabler of conceivable solutions.

5.2 | Efficiency

Quotes on the design theme "efficiency" show how important the affordability of novel, innovative solutions is for the BoP. Experts 1, 9, and 12 stress that "the village people cannot afford new batteries for energy storage." This is why there have even been "some initial trials of energy storage with small, new batteries at the Amazon. These attempts were abandoned because the villagers had to pay far too much for batteries that didn't have enough storage capacity" (member of Village Council 1). Therefore, "repurposing is a win-win situation. An approach that fits perfectly into the circular economy system, where the output of one system is used as input for another. They demonstrate this not only through material flows but also through efficient sector coupling" (Expert 1). This means that new cost-reduction potential can be realized by linking the automotive and energy sectors through the use of old car batteries for energy storage.

Repurposing additionally satisfies the "need for a reliable, 24-hour power grid" (Expert 9 and similarly other experts and community members) and the "need for a solution that functions reliably for at least 10 to 15 years, ideally reusing vehicle batteries" (community member and Experts 9 and 12). This results in two findings on the particular need for efficiency through "cost dispersion across different applications through repurposing" at the BoP (Subcategory 4 in Appendix C, see Table 2):

1. Second-life, respectively, repurposes approaches based on a coupling of different sectors, opening up considerable efficiency potentials beyond cost reduction in only one single sector.
2. Taking used car batteries for a second life for solar storage might bring the necessary efficiency to new business models at the BoP because it allows a cost dispersion across different repurposing applications.

With regard to economic feasibility, Expert 4 emphasizes that the diesel subsidies saved on the BoP should be redirected to energy storage through repurposing car batteries: "The initially subsidized use of used car batteries for storing solar energy could pay off in the medium term (in less than three years) and, unlike the competing diesel generators, provide free subsidies. The Brazilian government would only have to redistribute the subsidies." Expert 11 adds that, if the battery is not scrapped "after its use in the car," but can be sold for "perhaps around 60% of the original price, the battery holds a much higher value." This provides a further insight into the special feature of "cost allocation to different applications through reuse" at the BoP (Subcategory 4 in Appendix C, see also Table 2):

3. The repurposing solution pays for itself at the BoP after less than 3 years if the subsidies are diverted to diesel and large batteries.

With regard to standardization and scalability, Expert 1 (and similarly Expert 8) emphasize, among other things, that "standardization plays a pivotal role in ensuring the scalability and replicability of projects like these. By adopting standardized processes for battery collection, sorting, and installation, we would not only streamline operations but also enhance compatibility and efficiency." And Expert 1 adds: "Moreover, standardization fosters innovation by providing a framework for sustainable design and resource utilization. Embracing standardized protocols and interfaces not only facilitates interoperability but also instills confidence among stakeholders, paving the way for widespread adoption and impact." In any case, standardization and scalability are important for rolling out the novel idea of energy storage at the BoP in other regions of Brazil and in other countries around the world: "the more standardized it [a solution] is, the better it can be transferred, and it won't remain a single project because the idea is indeed very exciting and can be applied in many areas of the world since it's [an idea] that is useful everywhere, not just in the Amazon region" (Expert 1). Therefore, the scalability is not limited to the Amazon. "There are probably numerous regions and millions of people for whom an affordable additional storage solution using old car batteries could improve their quality of life and energy security" (Expert 6). From this, the following insights can be drawn, further differentiating "searching for standardization" and "searching for scalability" at the BoP (Subcategories 5 and 6 in Appendix C, see Table 2):

4. The systems should be as standardized as possible to keep complexity costs as low as possible and to enable scaling.

The four findings reveal an efficiency approach for repurposing for a second life at the BoP (summarized in Table 2). Substituting Linkage II between the antecedent "template of incumbents and others" and the design theme "efficiency" in the early business models analyzed so far (Figure 1) by "Framing and benchmarking to achieve efficiency without compromising novelty," "Efficiency" at the BoP does not require the same solution to be cheaper, but a different solution, in this case through repurposing.

5.3 | Complementarity

The interviewees confirmed the need for complementarity by "seeking bottom-up in the local context for opportunities" (Subcategory 10 in Appendix C, see Table 3) in view of the problems at the BoP. Expert 11, e.g., emphasizes that "existing structures must be used [...] for collaboration, [...] where batteries are to be refurbished and new facilities developed, installed, maintained, and repaired [...] and [that] the new networks are created primarily through solidarity." This underlines the importance of socially responsible value creation. However, the experts also see the need to create a basis for satisfying additional needs. They see "various benefits" for residents when using second-life batteries for solar storage "as well as for the entire country. Not only for residents directly affected by the electricity supply, but also for other residents" (Expert 12). This is because the new low-cost energy storage with used car batteries "is not a one-time thing.... with the on-set of electrification, the energy demand also increases" (Expert 6). They not only allow refrigerators to be operated around the clock even at the BoP to keep food and medicine cool within the villages, but there is also a need for energy

based on cheap battery buffered solar stations for "other applications such as … hospitals, emergency power supply, or energy buffering" (Expert 9). This results in two further insights into what "bottom-up search for possible applications in the local context" (Table 3) means through repurposing at the BoP:

1. A novel and efficient repurposing business model at the BoP must be found and implemented in a community of solidarity with local communities for socially responsible value creation.
2. The new business model at the BoP must have a growth flexibility insight outside the initial use case.

With regard to "interaction with non-market actors at the BoP" (as a further Subcategory 11 of the category "complementarity" in Appendix C), i.e., with (local) governments, non-governmental organizations, or local associations, respondents say that "a close community collaboration with villages, the provision of the second-life solar system and the installer is important. Here, public-private partnerships can help" (Expert 2), "because only through this collaboration we can achieve this overarching benefit that all stakeholders will have" (Expert 1). Also, "collaboration with NGOs or international aid organizations would be interesting to ensure scalability" (Expert 2). There is also an opportunity to initiate a stronger public–private partnership because functioning energy storage with second-life batteries will reduce the need for government subsidies. Not all existing diesel subsidies are needed to support the sustainable energy solution. The villages are thus no longer just recipients of state funds but partners in the development of cost savings in the cash-strapped public sector. This leads to a further insight into what complementarity means through "interaction with non-market players at the BoP" (see Table 3):

3. Interaction with "non-market actors at the BoP" as a true collaborative public–private partnership is possible.

This is why the interviewees also see the need to "establish an inclusive repurposing ecosystem" (Subcategory 12 in Appendix C). According to Expert 1, it is "a network [with] a win-win situation everywhere, thus establishing the foundations of an ecosystem. Therefore, we definitely have positive effects for everyone participating in this network, which is holistic from electricity generation to usage and with participation of all stakeholders in the regions." Expert 2 supplements that "furthermore, the Brazilian and the local government could be involved in the ecosystem and, in this process," as has already been pointed out, "redirect subsidies for diesel generator and diesel to support the second life battery system during an initial phase." However, not only non-market actors need to be part of the ecosystem, but "even customers see their role as stakeholders in ecosystems" as Expert 1 points out. Overall, "considering that the business models at the BoP are facing inefficient markets" (Expert 9) or even market failures (see Figure 2), "the creation of an ecosystem is very important for the introduction of (affordable) energy storage." Because, as, e.g., Expert 13 points out, "second-life repurposing solutions are of course too complex for only one company to handle." Nevertheless, it is important, according to Expert 9, "that either one company within this network or in the economy as a whole takes control of this (repurposing) process at the BoP" (also an "orchestrator," Sjödin et al. 2022), "perhaps by promoting standards that definitely need to exist for collaboration" (Expert 9). In order to achieve "complementarity" with "establish[ing] an inclusive repurposing ecosystem" especially at the BoP, two further insights can be noted (Table 3):

4. The development of ecosystems is the key to the implementation of novel and efficient solutions and corresponding business models, especially in inefficient markets and even more so in the event of market failure.
5. For novel solutions that also meet the efficiency requirements at the BoP, implementation must be accelerated on the one hand through coordinating individual needs of the consumers (complementarity in consumption) and on the other hand through pooling the strength of providers (complementarity in production), especially in inefficiently functioning or failing markets. This finding corresponds to the types of complementarities of Jacobides et al. (2018, 2266).

The five findings reveal the specifics of creating complementarity to implement repurposing for second life at the BoP (summarized in Table 3). Extending Linkage IV between the antecedent "stakeholder activities" and the design theme "complementarity" in the early business models analyzed so far (Figure 1) showed that by "enhancing complementarities by orchestrating new networks (ecosystems)," "complementarity" at the BoP due to repurposing is not linear but accelerates over time.

5.4 | Lock-In

At the BoP, repurposing for a second life creates a natural "lock-in" by "causing sunk costs" (Subcategory 1, see Appendix C), as such solutions are designed for the long term with replacement cycles of up to 12 years. Similarly, Expert 6 emphasizes that the village people "would heavily rely on this battery system because it's not being built as a temporary solution until power grids are restored, but rather as a permanent solution." This is also due to the transaction costs incurred when switching to such a solution as "for the local people, this would definitely imply a corresponding adjustment or, essentially, a very strong dependency on the functionality of this battery. So, if it works well and reliably, I believe people would rely on it extremely heavily" (Expert 1) because "any change to the interconnected solution would be expensive" (Expert 2). When considering villages in the Amazon, "it is also important to [...] establish a leasing model, where the batteries are recycled at the end of their [second] life" (Expert 7). This results in a first in-depth insight into the particular understanding of lock-in through repurposing for a second life with sunk costs specifically at the BoP (see Table 4):

1. The novel yet efficient repurposing business model with complementary users and "production" partners at the BoP

creates durable structures with high customer and partner commitment due to long replacement cycles and high sunk costs through leasing contracts.

Solutions "embedded in the social context at the BoP" and "integrated in the circular system" (Subcategories 2 and 3, see Appendix C) are also demanded by the interviewees. Expert 5 should be mentioned here, who emphasizes that the second-life battery energy storage solution "is a social progress [...], especially because the social dimension is embedded in the ecological one." This results in a second insight, combining Subcategories 2 and 3, see also Table 4:

2. When economically and ecologically sustainable solutions for storing solar energy in used car batteries are embedded in the social development of remote villages on the BoP, this leads to "sunk social costs."

These two findings reveal the specifics of creating a lock-in by repurposing for second life at the BoP (summarized in Table 4). Extending linkage I between the antecedent "goals to create and capture value" and the design theme "lock-in" in the early business models analyzed so far (Figure 1) by "balancing value creation for all stakeholders with value capture by the focused company," "lock-in" through repurposing at the BoP does not lead to a "simple lock-in" through customer and partner commitment, but to a "double lock-in" through additional involvement in social development (with economic and social sunk costs).

6 | Implications

Our investigation of the repurposing of used car batteries in a second life for solar-powered storage systems in off-grid regions at the BoP considers requirements for the specific interaction and the specific design of the four design themes in the development of these special early repurposing business models at the BoP. It thus extends the blueprint of early business models by Amit and Zott (2015), see Figure 1), which we already supplemented with the results of a critical review of relevant literature on business models at the BoP and for repurposing (Figure 2). Figure 2, therefore, summarized the specific opportunities and constraints at the BoP and roughly mentioned the special characteristics of the design themes already discussed. As 12 subcategories of the four design themes, these special characteristics guided our case study in Brazil. Figure 3 illustrates the condensed findings of our study on the design themes and thus offers a blueprint that concretizes the rough framework of such a blueprint in Figure 2 and clearly highlights the special features of an early repurposing business model at the BoP: "Novelty" as an enabler of conceivable solutions must increase the willingness to pay and thus make a higher sales price possible, while "efficiency" through different instead of cheaper solutions, here through repurposing, must reduce the opportunity costs and therefore the purchase price. Only then can the difference between sales price and purchase price be extended by increasing (accelerating) "complementarity" of the partners and consumers of repurposing for the BoP over time and by a "double lock-in" through an economic commitment and involvement in social development. More concretely, the insights (right-hand columns) from Tables 1–4 can be summarized (see Figure 3):

- "Novelty" increases willingness to pay and raises sales prices as an enabler of conceivable (repurposing) solutions at the BoP when they empower inhabitants in remote off-grid villages to use their minimal wages for craftswork and demonstrating initiative; they also have a low risk of technical substitution, can repurpose existing technologies in a new context, and are very robust and modular. This is necessary in view of very low (even aggregated) purchasing power and high transaction costs due to inconsistent government regulations and hardly any relevance to the low labor costs given the capital intensity of the solar system with used battery storage.
- "Efficiency" at the BoP requires a significant reduction in purchasing price and opportunity costs, a different (novel) repurposing solution, and the coupling of various sectors that open up considerable efficiency potentials beyond cost reduction in one sector. It also permits cost dispersion across different repurposing applications and amortizes relatively quickly if subsidies are redirected to the new (solar) solution. When the systems are as standardized as possible to keep complexity, scaling is made possible.
- "Complementarity" accelerates over time, when a novel and efficient repurposing business model at the BoP is found and implemented in a community of solidarity, has flexibility for growth both inside and outside its initial use, interacts with "non-market" entities in public–private partnerships and develops an ecosystem in view of inefficient markets and market failure through coordinating individual needs of the consumers and pooling the strengths of the provider. This creates the potential for additional willingness to pay on the part of consumers.
- "Lock-in" through repurposing at the BoP signifies a "double lock-in" through additional involvement in social development, which creates durable structures with high customer and partner commitment due to long replacement cycles and high (economic) sunk costs through leasing contracts, but also "social sunk costs" when embedded in the social development of remote villages on the BoP. This keeps the purchase price and opportunity costs under control.

Figure 3 offers not only an abstract representation of the extension of the theoretical consideration of early business models for the special features of repurposing at the BoP, but also a guide for practical implementation not only in Brazil but also in other countries with population groups at the BoP where there is solar, wind, and/or water energy, such as India or Namibia. This makes it a blueprint that can be rolled out across different locations for multinational companies. Furthermore, the blueprint can also be transferred to other efficiency mechanisms—beyond repurposing—at BoP.

In addition, our study clearly shows differences in the development of repurposing business models at the BoP compared with those in developed countries: Repurposing at the BoP is a combination of the novelty of a low-maintenance solar (or

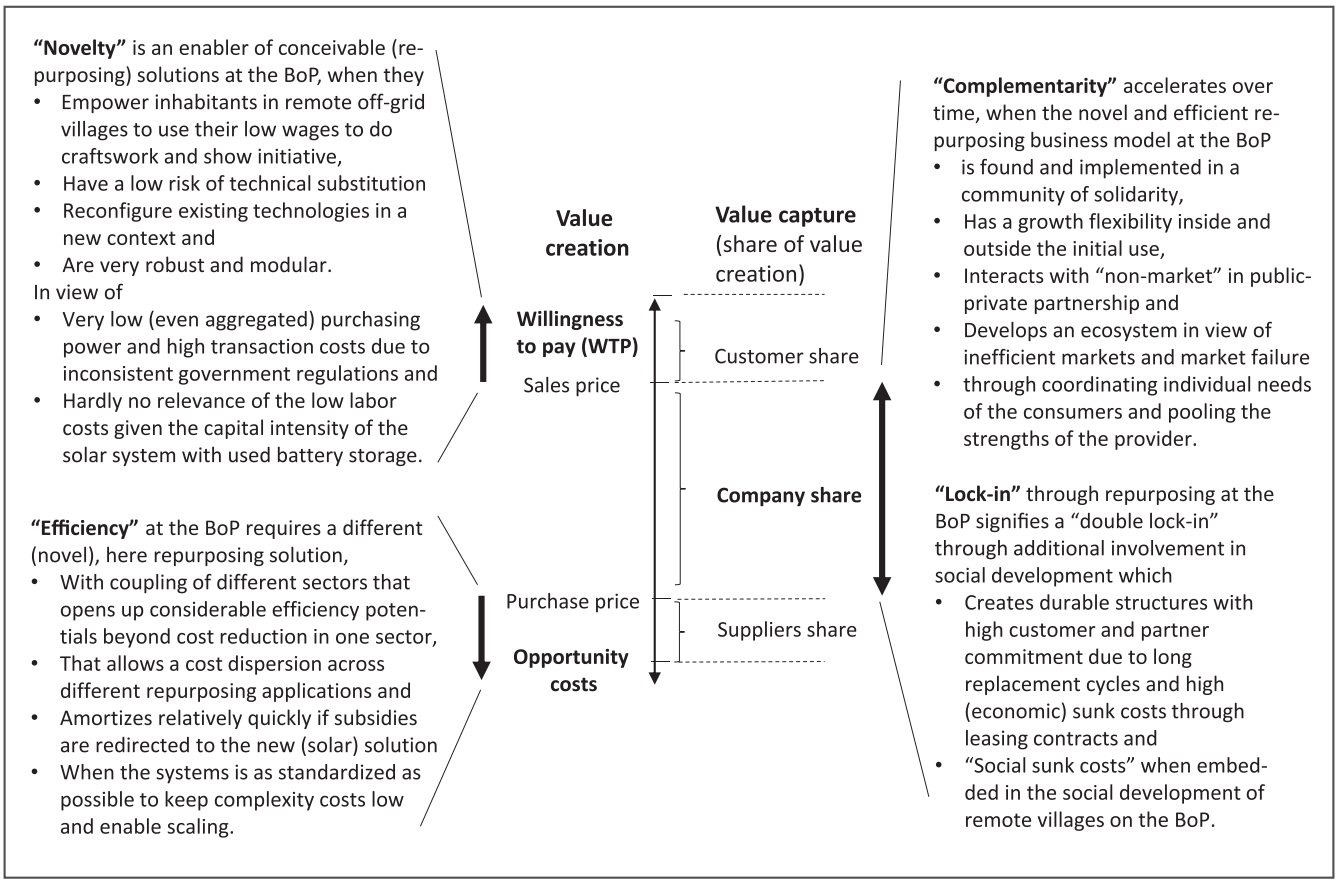

FIGURE 3 | Blueprint of an early repurposing business model as a result of the case study (Source: own extension of this Figure 2).

wind) powered energy supply in countries with an abundance of solar (or wind) energy with the necessary efficiency for the poor population through cheap storage with used second-life batteries. Because unlike the demand for sufficiency (e.g., Jungell-Michelsson and Heikkurinen 2022) in developed countries, the BoP's lowering of standards through reuse or repurposing at the BoP is not sufficiency but rather the fulfillment of basic needs.

The results of our study thus also show a truly sustainable form of value creation that has rarely existed in this form in reality to date, namely, the combination of value creation with limited resources ("frugal innovation," Albert 2019; Radjou et al. 2012) and socially responsible value creation, which also pays off, at least when subsidies are redirected. It thus lies in the middle of the field of tension between the three pillars of sustainability (social, ecological, and economic, e.g., Lüdeke-Freund et al. 2018; Oskam et al. 2021), in which one pillar is usually neglected (e.g., the social dimension in repurposing and the ecological dimension in "social missions" such as socio-economic empowerment).

At the BoP, there is no need for radical novelty/innovations as often as in developed countries, but for adapted, incremental innovations that help users to help themselves, for example, by empowering craftsmanship and entrepreneurship, such as through a stable, low-cost, and low-maintenance energy supply. However, novelty at the BoP must be enabled by efficiency, as affordable solutions are essential. This differs from established models where novelty and efficiency are balanced rather than intertwined (Amit and Zott 2015). The emphasis on affordability is in line with the theory of "disruptive innovation," where simpler, more affordable solutions can displace established technologies (Christensen et al. 2018). It is also important to understand the specific energy needs of the community, guided by the principles of "human-centered design" (Brown and Wyatt 2010) and "demand-driven innovation" (Olson 2009).

Finally, at the BoP, the involvement of non-market players and the promotion of solidarity between stakeholders is even more important than in developed countries, where market forces predominantly shape ecosystem development (Jacobides et al. 2018). This emphasis on "inclusive innovation" (Heeks et al. 2014) recognizes the importance of social embeddedness and local knowledge in achieving sustainable development at the BoP.

7 | Limitations and Outlook

Our study highlights the transformative potential of circular economy principles and underscores the need for collaborative ecosystems and public–private partnerships to drive innovation at the BoP (Hansen and Revellio 2020; Kirchherr et al. 2017). However, several limitations must be acknowledged, which should be taken into account in future research.

First, while the proposed blueprint provides a comprehensive framework for early business model design, it relies on a single case study, which may limit its generalizability. Future studies

could expand the scope to include multiple cases across diverse geographical regions and industries to validate and refine the model.

Secondly, it was assumed that among the antecedents of these business models, the goals were to create and capture value through the repurposing of batteries for renewable energy storage, but also the general constraints and opportunities in the corporate environment (low purchasing power, inefficient markets, pressure towards adapted innovation) are similar in other regions at the BoP (e.g., Namibia or India), so the proposed early business models at the BoP are also important there, and this offers a strategic option for multinational companies in many BoP markets. However, it was not examined as:

- To what extent the specific constraints and opportunities in the corporate environment differ (e.g., the availability of second-life batteries as well as the regulatory environment, market structures, and technological infrastructure) and
- Whether the design themes of "complementarity" and "lock-in" differ because of different actors, competitors (established companies and others), and stakeholders.

Future research should therefore also investigate the extent to which some of the antecedents and all the design themes (Figures 1–3) are culture-free or culture-bound (based on Hofstede 1980).

Finally, the study highlights the importance of ecosystem coordination but does not provide detailed insights into the roles and responsibilities of various stakeholders. Developing a more detailed governance structure for these ecosystems could provide practical guidance for implementation (Adner 2017; Dyer et al. 2018).

In terms of outlook, the proposed blueprint represents a promising step towards sustainable business models for the BoP. By addressing key constraints and leveraging local opportunities, it offers a pathway for creating economic, social, and ecological value. Future research should continue to build on this foundation, exploring innovative applications and adaptive strategies that further enhance its impact and scalability.

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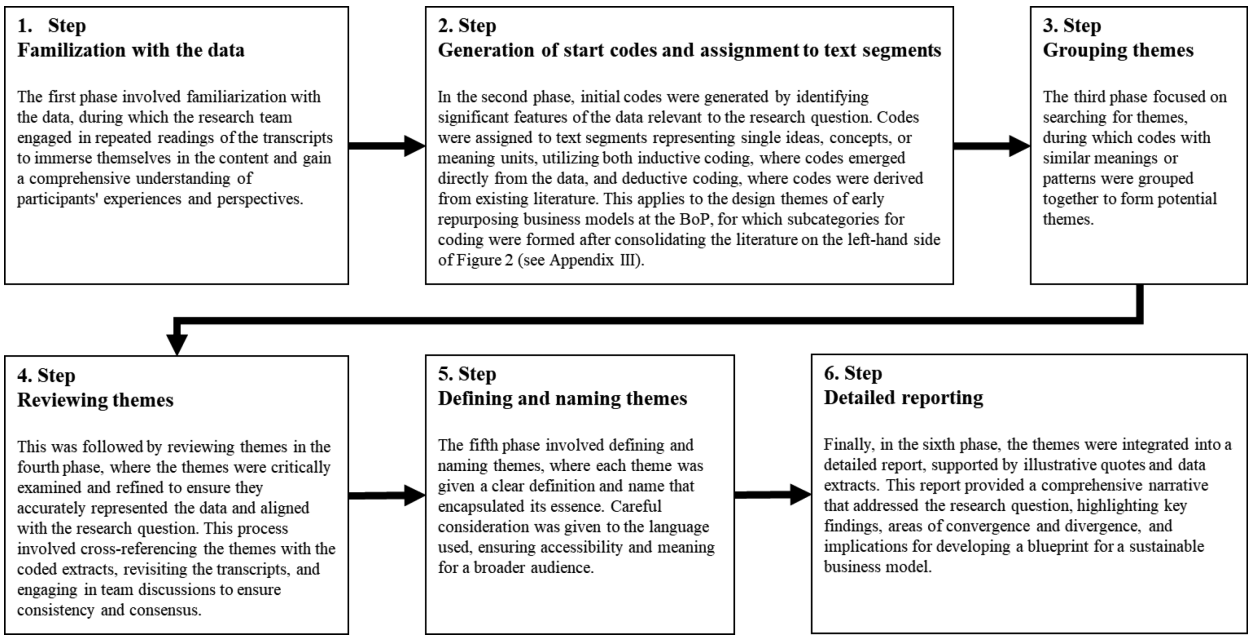
Appendix A

Experts interviewed.

Expert	Expertise	Relevance to the study
Expert 1	Professor specializing in sustainability, leadership, and supply chain management	Brings extensive knowledge of sustainable business models and supply chain optimization, crucial for developing a viable and scalable business model for battery repurposing.
Expert 2	Professor specializing in sustainability and socio-technical transformation	Offers expertise in understanding the social and technical dimensions of technological change, particularly relevant for analyzing the adoption and integration of repurposed batteries in remote communities.
Expert 3	Engineer and research associate specializing in second-life battery applications	Provides in-depth technical knowledge of second-life battery technologies, including performance characteristics, safety considerations, and potential applications.
Expert 4	Engineer and research associate specializing in second- and multi-life battery repurposing	Possesses a broad understanding of battery repurposing across various applications, offering insights into best practices, technical challenges, and emerging trends in the field.
Expert 5	Scientist (Ph.D.) specializing in sustainability, mobility, and development aid	Brings a multidisciplinary perspective, combining expertise in sustainability, mobility solutions, and development aid, essential for understanding the broader context and impact of the proposed solution.
Expert 6	Engineer and research associate specializing in battery repurposing and technology	Offers specialized knowledge of battery technologies and repurposing processes, including testing, refurbishment, and integration into new applications.
Expert 7	Professor of engineering mechanics and numerical methods with experience as a development engineer for high-voltage batteries and fuel cells in the automotive industry	Provides expertise in the design, testing, and safety assessment of high-voltage battery systems, crucial for ensuring the reliability and safety of repurposed batteries in a new context.
Expert 8	Engineer and research associate specializing in high-voltage lithium battery testing	Brings practical experience in testing and evaluating the performance and safety of lithium-ion batteries, contributing to the quality control and risk assessment of repurposed batteries.
Expert 9	Professor specializing in solar photovoltaics	Offers expertise in the design and implementation of solar energy systems, essential for integrating repurposed batteries into off-grid energy solutions for remote communities.
Expert 10	Professor in the department of electricity with a Ph.D. in informatics and an M.Sc. in electrical engineering	Brings a broad understanding of electrical engineering and informatics, relevant for the technical planning, control, and optimization of the proposed energy storage solution.
Expert 11	Professor in the department of electricity with a Ph.D. in electrical engineering	Provides specialized knowledge of electrical power systems and their application in rural and remote contexts, contributing to the design and implementation of a reliable and efficient energy solution.
Expert 12	Engineer working at the Institute for Decentral Electrification, Entrepreneurship, and Education, with expertise in development aid and electrification	Offers a unique combination of technical, entrepreneurial, and development-oriented expertise, crucial for understanding the challenges and opportunities associated with decentralized electrification projects in developing countries.
Expert 13	Engineer and research associate specializing in second-life battery applications	Provides in-depth technical knowledge of second-life battery technologies, including performance characteristics, safety considerations, and potential applications.
Expert 14	Engineer and research associate specializing in electric mobility, charging infrastructure, and battery technology	Brings expertise in electric mobility and battery technologies, particularly relevant for understanding the sourcing, logistics, and management of used batteries for repurposing.

Appendix B

Thematic analysis (according to Braun and Clarke 2006).



Appendix C

Business model design themes with subcategories for interviews.

Business model design themes with subcategories	
Lock-in	1. Leveraging sunk costs 2. Embedded in the social context at the BoP 3. Integrated in the circular system
Efficiency	4. Cost dispersion across different applications through repurposing 5. Searching for standardization 6. Searching for scalability
Novelty	7. Countering constraints at the BoP 8. Taking opportunities at the BoP with special repurposing solutions 9. Creating innovative adapted repurposing solutions for the BoP
Complementarity	10. Seeking bottom-up in the local context for opportunities 11. Interacting with non market actors at the BoP 12. Establishing an inclusive repurposing ecosystem