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Backcasting the Future of the Automotive Industry: Leveraging Digital Technologies for the Circular Economy

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Abstract:

The automotive industry faces environmental challenges due to fossil fuels reliance and linear production models. Transitioning to a circular economy (CE) is essential for reducing emissions and achieving sustainability. This study uses backcasting to envision a circular automotive industry by 2050, aligned with the European Green Deal's carbon neutrality objectives. Our envisioned future leverages digital technologies like AI, digital twins, and product passports to enhance data sharing, traceability, and decision making across the supply chain. We examine how these technologies improve lifecycle management of electric vehicles, enhance circularity in design and manufacturing, and ensure transparency from production to end-of-life. While these technologies extend product lifecycles and minimize waste, transitioning towards circularity presents challenges such as data sharing, emphasizing the need for collaborative industry platforms. By engaging key stakeholders, we developed a pathway from the current state to the envisioned circular future. Focusing on CE principles, the study seeks to foster a systemic shift towards circularity, bridging the gap between information systems and CE research. Strategic policy interventions and cooperative frameworks are recommended to enable the transition. The paper contributes insights into digitalization's impact on CE, providing actionable strategies for industry stakeholders aiming to implement sustainable practices amid global resource constraints.

Keywords: Circular Economy, Digital Technologies, Backcasting, Automotive Industry.

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1 Introduction

Industrial production is rapidly approaching – if not already exceeding – the Earth's biophysical limits, thereby intensifying an environmental crisis that scholars attribute to decades of "take-make-dispose" practices (Zeiss et al., 2021). Calls for a decisive transition toward a circular economy (CE) – one that retains materials and value within closed loops – have therefore grown increasingly urgent (Khalifa et al., 2022). Few industries matter more in this transition than the automotive industry. Road transport accounts for roughly one quarter of global CO_2 emissions, with passenger vehicles constituting a major share of this footprint; in addition, the automotive industry generates emissions across its value chain through material extraction, manufacturing, and end-of-function processing. Without concerted action, scenario-based analyses suggest that emissions associated with today's mobility and production patterns could increase substantially toward 2030 (Aguilar Esteva et al., 2021; Yao et al., 2024). Electrification is necessary but not sufficient to address this: electric vehicles (EVs) rely on lithium, nickel, cobalt, and rare-earth elements whose extraction creates new environmental and geopolitical vulnerabilities (Duan et al., 2024; Takimoto et al., 2024). Recent modelling nonetheless shows that a portfolio of CE strategies – reuse, remanufacture, recycle, and recover – could lower primary material demand in the automotive industry by up to 32% by 2035 and 53% by 2050 while generating ecological, economic, and social value (Duan et al., 2024; Rizvi et al., 2023; World Climate Foundation, 2021).

Ambitious regulation amplifies this pressure. The European Green Deal and the Circular Economy Action Plan (CEAP) set explicit 1.5°C-consistent targets for a carbon-neutral, resource-efficient automotive industry (European Commission, 2020). Practice, however, remains uneven. Germany, for instance, recovered 97% of its 379,000 end-of-life (EoL) vehicles in 2021, yet mostly as undifferentiated bulk material; critical components and high-value elements were largely lost (Prochatzki et al., 2023; Umweltbundesamt, 2024). Although state-of-the-art recycling plants can now reclaim up to 95% of cobalt, nickel, and manganese and close to 90% of lithium from shredded battery "black mass", fewer than 10% of EoL EV batteries in the European Union (EU) reached such facilities in 2023 – pointing to a collection rather than a processing bottleneck (Transport & Environment, 2024). At the same time, about 98,000 used vehicles left the EU annually between 2018 and 2022 for markets in Africa, further depleting European resource loops (BMUKN, 2022; Ragnitz, 2024).

Material-centric recycling, although vital, is therefore insufficient. Preserving *functional* value – whole batteries, motors, control units – requires orchestration across the entire supply chain rather than firm-level optimizations (Trevisan et al., 2022). Emerging "battery passports" suggest that transparency, traceability, and accountability can support such orchestration (Berger et al., 2022), yet seamless data exchange and joint decision-making remain open challenges (Mügge et al., 2023; Zeiss et al., 2021).

Digital technologies are increasingly recognized as essential to achieving industry-level circularity (Winkelmann et al., 2024). Unlike traditional supply-chain IT, which primarily streamlines internal logistics, next-generation infrastructures – digital product passports (DPPs), digital twins, and federated data spaces – enable cross-organizational, secure, and sovereign data sharing, thereby generating real-time lifecycle insights and fostering (semi-)autonomous CE decisions (Rilling et al., 2023). In what follows, we define the *European automotive industry* as a tightly coupled network of OEMs and tiered suppliers that design, produce, and sell passenger vehicles, and that additionally encompasses ecosystem actors, such as platform operators, energy and logistics partners, and policymakers. While the industry shapes physical material flows, the ecosystem co-creates the digital, regulatory, and service infrastructures that render circularity feasible (Jacobides et al., 2018; Porter, 2008).

Recent flagship initiatives underscore this digital turn. *Gaia-X*[1] (launched in 2019) seeks to establish a federated, transparent European data infrastructure, mobilizing more than 300 industrial, academic, and governmental actors (Otto et al., 2022). Building on this foundation, *Catena-X*[2] (initiated in 2021) aims to establish an interoperable data space tailored to automotive needs; its implementation partner, *Cofinity-X*[3], already provides reference applications for traceability and sustainability reporting. Together, these projects illustrate how such secure data sharing architectures can redefine value creation.

[1] https://gaia-x.eu/ (accessed 25/05/2025)
[2] Catena-X und Gaia-X: Eine gemeinsame Vision für Datenräume. https://catena-x.net/de/vision/gaia-x (accessed 25/05/2025)
[3] https://www.cofinity-x.com/ (accessed 25/05/2025)

Artificial intelligence (AI) acts as a further accelerant. By analyzing complex datasets and predicting material flows or component failures, AI can fine-tune reuse and recycling decisions beyond the reach of conventional information systems (IS) (Kaggwa et al., 2024; Uwaoma et al., 2024). Yet despite promising proofs of concept, we still lack robust empirical knowledge of *how* such technologies integrate into real-world CE ecosystems and *under what conditions* they foster durable collaboration among diverse stakeholders (Langley, 2022; Petrik & Haerer, 2024). In particular, research has only begun to explore how economic objectives can be reconciled with circularity principles at scale.

Against this backdrop, our study adopts a *backcasting* approach – working backward from a desired 2050 end state – to investigate the role of current and emerging digital technologies in steering the European automotive industry toward full circularity. Specifically, we ask:

> **RQ: How might current and emerging digital technologies facilitate the adoption of CE practices in the future of the European automotive industry?**

We pursue three objectives to address this question. First, we identify and evaluate the portfolio of digital technologies – AI, digital twins, DPPs, and more – that hold the potential to advance CE practices. Second, we map the contribution of canonical CE strategies (reduce, reuse, repair, remanufacture, recycle) across the automotive product lifecycle. Third, we assess the opportunities and barriers to integrating digital technologies within CE frameworks, with special attention to data sharing, decision making, and stakeholder collaboration. Our scenario-based backcasting method aligns these objectives, generating a roadmap that links today's technological and organizational choices to a 2050 vision of circularity.

The remainder of this paper is structured as follows: Section 2 reviews CE principles and clarifies the enabling role of digital technologies. Section 3 details our backcasting methodology. Section 4 then presents our findings: Section 4.1 outlines a 2050 sustainability target for the automotive industry; Section 4.2 diagnoses the current state of CE practices and digital integration; Section 4.3 envisions two images of the future of a circular automotive industry in 2050; and Section 4.4 outlines the pathways required to reach them. Finally, Section 5 discusses theoretical, managerial, and policy implications and proposes directions for future research.

2 Background

2.1 Circular Economy

The CE marks a paradigmatic shift away from the dominant linear "take-make-dispose" logic. Instead of tying economic growth to the continual extraction of virgin resources and the accumulation of waste, CE seeks to *slow*, *narrow*, and *close* resource loops, thereby decoupling prosperity from environmental degradation (Ghisellini et al., 2016; Kirchherr et al., 2017). At the core of this vision are the widely recognized 4R strategies – reduce, reuse, recycle, and recover – which collectively delineate a roadmap for achieving industrial sustainability.

Reduce aims to minimize both the material and energy inputs at the design stage and throughout production processes (Ghisellini et al., 2016). Automotive manufacturers increasingly rely on data-driven design tools that deliver real-time insights into material footprints, thereby highlighting opportunities to achieve lightweight construction or component downsizing without sacrificing performance (Arnemann et al., 2023). By integrating a life-cycle assessment dashboard or AI-based optimization algorithms early in the engineering workflow, firms can systematically eliminate waste before it occurs (Junk & Rothe, 2022; Mügge et al., 2024).

Where reduction reaches its limits, *reuse* extends product lifetimes through repair, refurbishment, and remanufacturing (Blomsma & Brennan, 2017; Ellen MacArthur Foundation, 2012). In the automotive domain, DPPs and blockchain-enabled part histories facilitate the assessment of a component's potential residual value, streamline reverse-logistics decisions, and support service-oriented business models (Kim et al., 2025). Hence, reuse not only mitigates the need for virgin resources but also stimulates secondary markets for repaired, refurbished, or remanufactured parts (Pohlmann et al., 2024).

Recycle converts EoL materials into new inputs, supporting a closed-loop system that minimizes raw material extraction (Geissdoerfer et al., 2018). Effective recycling in automotive settings presupposes design for disassembly and the availability of granular data on material compositions at product, component, and part levels (Pohlmann et al., 2024; Tian & Chen, 2014). Internet of Things (IoT) sensors and computer vision systems increasingly facilitate automated sorting, thereby enhancing both throughput and purity of recycled material streams (Kim et al., 2025).

Only when reduction, reuse, and recycling have been exhausted does *recover* extract residual value, typically via energy generation from incineration (Kirchherr et al., 2017). Although recovery should remain the strategy of last resort, advanced decision-support systems help organizations determine when recovery becomes unavoidable, ensuring that circularity goals are preserved even in suboptimal scenarios (Vitorino De Souza Melaré et al., 2017).

While the 4Rs provide a robust conceptual framework, operationalizing them across global value chains demands unprecedented levels of collaboration, transparency, and data stewardship (Jensen et al., 2023). These challenges are amplified in the automotive industry, where geographically dispersed suppliers, evolving regulatory regimes, and legacy enterprise IS complicate cross-organizational information flows. Consequently, the successful implementation of CE strategies depends on digital technologies, such as IoT platforms, cloud analytics, and AI-driven decision-support systems, that enable the collection, integration, and use of lifecycle data to inform design, operation, reuse, and EoL decisions across the automotive value chain (Hoppe et al., 2024b).

2.2 Digital Technologies in CE

Digital technologies constitute the connective fabric of the CE not merely as isolated tools, but as interdependent layers that structure how circular information is generated, shared, and used (Zeiss et al., 2021). Their importance is particularly pronounced in the automotive industry, where real-time data exchange and cross-supply chain integration are prerequisites for circularity (Hoppe et al., 2024b). Accordingly, we distinguish three mutually reinforcing technological layers – data collection, data integration, and data analysis – and explain how their interplay enables, but also constrains, the transition to circular ecosystems.

Data collection technologies – including radio frequency identification (RFID), the IoT, and blockchain – create the foundational visibility of material and information flows. RFID tags and IoT sensors embedded in vehicles or sub-assemblies capture granular usage and condition data throughout production, use, reuse, and eventual recycling or recovery (Rossi et al., 2020; Schöggl et al., 2024). Blockchain can further augment traceability by attaching tamper-resistant provenance records to physical objects (Kim et al., 2025). Yet, as we elaborate next, the mere accumulation of data is insufficient; its value materializes only when heterogeneous datasets are reliably linked across actors and lifecycle phases.

Data integration technologies – notably product lifecycle management systems and digital industrial platforms – address this challenge by harmonizing distributed datasets and exposing them through shared interfaces. Product lifecycle management environments maintain persistent digital identities for products, components, and materials, while digital industrial platforms provide multi-tenant infrastructures for secure data and service exchange (Pauli et al., 2021). From a socio-technical perspective (Bostrom and Heinen, 1977), successful integration depends on aligning technical standards with governance arrangements that balance transparency and confidentiality – an equilibrium that remains unresolved in many circular initiatives (Hoppe et al., 2024a). Closing this gap requires IS research on platform architectures and access control regimes that protect proprietary knowledge while encouraging cross-firm collaboration.

Moving from integration to insight, *data analysis* technologies such as AI, machine learning, and big data analytics transform raw inputs into actionable knowledge. Predictive models can estimate the residual life of components, forecast the availability of EoL vehicle parts, and optimize reverse-logistics routes. Nevertheless, circular settings impose two under-researched requirements. First, decision-support systems must operate in (near) real time so that reuse or recycling decisions keep pace with volatile supply systems. Second, models must remain robust under concept drift, i.e., the gradual shift in the statistical properties of input data over time, which threatens the validity of predictions in dynamic ecosystems (Baier et al., 2019). Addressing these issues calls for adaptive AI pipelines that continuously retrain on fresh data and incorporate explicit feedback from domain experts.

Realizing the full potential of data collection, integration, and analysis technologies is ultimately an ecosystem-level endeavor. Technical interoperability must be complemented by organizational routines and cultural norms that encourage data sharing, joint problem-solving, and trust-based governance. When digital infrastructures and CE strategies are co-designed, firms can collectively forge more resilient, transparent, and resource-efficient supply networks.

3 Methodology

3.1 Backcasting Methodology

Backcasting is a strategic planning methodology widely used in future studies that begins with a normative vision and then works backward to identify the milestones, decisions, and actions required to reach that end state (Dreborg, 1996; J. B. Robinson, 1982). Developed initially in energy research and later embraced across sustainability studies (Höjer & Mattsson, 2000; Quist et al., 2011; Vergragt & Quist, 2011), backcasting differs fundamentally from forecasting, which projects trends linearly from the present. By contrast, backcasting purposefully detaches from prevailing trajectories, positing that transformative, rather than incremental, change is often necessary to tackle grand challenges such as carbon neutrality or circularity (Barrella & Amekudzi, 2011; J. Robinson et al., 2011).

Backcasting's normative anchoring offers two distinct advantages. First, in IS contexts where technological evolution is rapid and empirical regularities are scarce, it provides researchers with a structured lens through which to envision technology-enabled futures despite uncertain data (Niederman, 2023). Second, backcasting provides decision-makers with a roadmap that highlights which interventions, governance mechanisms, and capability investments are required today to realize desirable digital futures tomorrow. Accordingly, our study leverages backcasting to explore how, e.g., AI, digital twins, and DPPs might enable the automotive industry's transition toward circularity by 2050.

The methodological rigor of backcasting stems from an explicit sequence of analytical steps. We therefore adapted the four-phase framework proposed by Höjer et al. (2011) – (1) target definition, (2) target analysis, (3) images of the future, and (4) pathway development – to our research setting. Table 1 juxtaposes each canonical step with our implementation, explaining where and why deviations were necessary. By making these adaptations transparent, we strengthen the reliability and transferability of our findings.

Table 1. Alignment of Backcasting Approach with Höjer et al (2011)

	Backcasting step	Höjer et al. (2011)	Our implementation	Output of the step	Divergence & justification
1	Target Definition	Define a normative, long-term target based on sustainability challenges; often guided by environmental or societal goals.	Defined the target of achieving a carbon-neutral automotive industry by 2050 through CE strategies and digital technologies. Grounded in regulatory frameworks.	Clear and policy-aligned target framing the direction of backcasting of the European automotive industry.	Anchoring the normative target in regulatory frameworks and digital capabilities represents a situated translation of Höjer et al.'s (2011) abstract goal-setting, ensuring contextual alignment with institutional and technological realities in the European automotive industry.
2	Target Analysis	Analyze the current situation, including structural barriers, stakeholder perspectives, and systemic conditions. Suggested data sources include stakeholder input and existing literature.	Combined qualitative insights from 14 semi-structured expert interviews with stakeholders from the automotive industry followed by a literature review.	Identification of readiness gaps, systemic barriers, and alignment between research and practitioner discourse.	We conducted interviews prior to the literature review to validate stakeholder-informed themes emerging from the industry's current state. This approach enabled inductive grounding and helped refine the literature scope for contextual relevance.
3	Images of the Future	Develop multiple future scenarios through	Developed two future images via internal iterative	Scenario narratives aligned with the	The scenario co-creation via iterative workshops supports

		stakeholder involvement, typically in participatory workshops. Use creative and exploratory methods to challenge assumptions and expand vision.	design, followed by validation and refinement in a 1-hour participatory workshop with 9 industry and research experts.	2050 CE target for the European automotive industry, integrating key digital technology enablers and illustrating changes in business models and operational practices.	participatory visioning and boundary-spanning design to ensure plausibility.
4	Pathway Development	Identify actions and milestones needed to reach the target from the present state. Validate with relevant stakeholders to ensure feasibility. Emphasis on alignment between long-term goals and short-term decisions.	Developed pathways through author team synthesis sessions. Validated via a 1-hour workshop with 5 CE and automotive industry experts to assess operational feasibility and industry fit.	Four phases for reaching the target including technological, policy, and organizational milestones by 2050.	Using visual synthesis and expert validation integrates sensemaking with practical feasibility, bridging long-term visions with actionable system change.

3.1 Applying and Operationalizing Backcasting Methodology

To develop a strategic roadmap guiding the European automotive industry toward carbon neutrality by 2050, we apply backcasting to our empirical context. This approach is well suited to the research setting, as the targeted future state hinges on the combined implementation of circular economy principles and digital technologies, which are becoming mandatory across automotive supply chains. Following the four-step backcasting framework outlined above, we draw on different data sources at each stage; an overview of these sources is provided in Table A1 in the Appendix.

Step 1: Target Definition. To establish a precise, policy-aligned target, we focus on regulatory cornerstones such as the European Green Deal and the CEAP that operationalize global sustainability goals first explicated in the Paris Agreement, which already mandate industry stakeholders to reduce emissions and resource intensity; our defined target, therefore, aligns with – and extends – these policy trajectories. Particular emphasis is placed on digital technologies such as the DPP, instantiated most visibly through the upcoming battery passport for EVs (European Commission, 2020). By embedding granular lifecycle data in machine-readable formats, the DPP is envisaged as the connecting element enabling collaboration, verification, and iterative optimization across organizational boundaries.

Step 2: Target Analysis. Having articulated a clear target, we next examine the automotive industry's ability to realize that ambition. Step 2, therefore, evaluates the present-day feasibility of a transition toward a CE by triangulating two sources of information: (1) semi-structured stakeholder interviews and (2) an exploratory literature review. The dual approach allows us to juxtapose practitioners' perceptions with scholarly and industry knowledge, generating a clear picture of current readiness and residual gaps.

Stakeholder interviews. Semi-structured interviews are routinely employed in the early stages of backcasting to surface diverse perspectives before more interactive modes – such as workshops or focus groups – refine the vision (Höjer et al., 2011; Kishita et al., 2024). Guided by this logic, we conducted 14 interviews across two rounds in March 2023 with representatives of eight organizations spanning manufacturers, suppliers, and remanufacturers (see Table 2). The first round (n=8) mapped the roles of these actors and their stated commitment to CE, while the second round (n=6) revisited the same organizations to probe prerequisites for secure, efficient data and information sharing.

Participants were recruited through purposive sampling for their domain expertise and positional insight into circular practices in the automotive industry. Each 33-68-minute interview followed a semi-structured protocol that explored the societal mechanisms linking digital technologies to CE adoption in the automotive industry. All interviews were audio-recorded with consent, transcribed verbatim, and analyzed using the Gioia methodology (Gioia et al., 2013). Inductive first-order coding captured respondents' vocabulary; subsequent aggregation into second-order themes and overarching dimensions revealed patterns in circular and digital mechanisms shaping the sector.

Table 2. Overview of Interviewees

Round	ID	Role	Background	Experience	Length
1	I1	Team Leader	Business	4 years	0:58 h
2					0:58 h
1	I2	Research Vice President	Business, Development	23 years	1:03 h
2					0:50 h
1	I3	Key-Account Manager Research Student	Business, Development	4.5 years 0.5 years	1:01 h
2					0:48 h
1	I4	Head of Software Engineering	Development	8 years	0:33 h
2	I5	Mechanical Engineer	Development	7 years	0:53 h
1	I6	PhD Environmental Planning and Engineering	Research	4 years	0:46 h
1	I7	Analyst Energy Efficiency Programs	Business, Development	20 years	1:04 h
2					1:00 h
1	I8	Head of Remanufacturing	Business	5 years	0:56 h
2					1:00 h
1	I9	PhD Resource Technology and Systems	Research	3 years	1:08 h

Literature review. To validate and extend interview-derived insights, we executed an exploratory literature review in July-August 2024. Contrary to conventional sequencing, the review followed the interviews; this inversion avoided imposing ex-ante assumptions and allowed empirical findings to calibrate the search scope. Searches in Web of Science and Scopus – the most common databases among CE researchers due to their broad coverage of interdisciplinary research, particularly in environmental science, business, and economics (Ferasso et al., 2020; Homrich et al., 2018; Zhu & Liu, 2020) – combined the terms "circular economy", "automotive industry", and "digital technologies", yielding 92 journal articles. Title screening removed 46 items, abstract screening a further 30, and forward- and backward searches added three, resulting in 19 articles that satisfied the criteria of thematic relevance and methodological rigor (see Table A2 in the Appendix for the full list). Complementary grey literature – comprising a total of 8 position papers, industry reports, association white papers, and consultancy analyses from leading automotive and technology firms – was also analyzed to inject real-world pragmatics often absent from academic debates, listed in Table A3 in the Appendix.

The combination of interview and literature findings allows a comprehensive assessment of the automotive industry's readiness. Interview themes revealed cautious optimism tempered by concerns over data sharing governance. At the same time, the literature confirmed these tensions and highlighted emergent digital enablers (e.g., secure data spaces) that have yet to achieve sector-wide diffusion. The evidence collectively underscores both momentum and material gaps. Addressing these issues is imperative for the continued viability of the envisioned CE target.

Step 3: Images of the Future. Building on the feasibility insights derived in Step 2, this step projects the European automotive industry forward to 2050 and sketches two future scenarios. In line with backcasting logic, these "images of the future" are not forecasts but aspirational constructs that describe what the industry *could* look like if foundational CE principles were fully supported through digital technologies. Three sequential activities lead this step: (1) iterative author-team visioning, (2) an expert workshop, and (3) a structured synthesis via Sinek's Golden Circle framework.

Iterative author-team visioning. The process began with a series of internal creative sessions in early 2024. Drawing directly on empirical findings from Steps 1 and 2, we circulated memos, produced rough storyboards, and experimented with visual canvases to surface potential outcomes of successful CE-driven transformation, realizing the stated target. This repetitive "sense-making loop" (Weick et al., 2005) enabled us to explore the boundary conditions – technological, regulatory, and behavioral – within which any 2050 vision must reside. Interim outputs were deliberately provisional; their primary function was to facilitate subsequent dialogue with experts.

Expert workshop. To refine and expand the target and provisional future images, we conducted a one-hour workshop in August 2024 with nine participants spanning IS scholarship as well as manufacturing and technology practice. Although scheduling constraints prevented the participation of all relevant automotive stakeholders, most panelists were already familiar with the project aims through prior informal exchanges. Following a participatory workshop logic (Kishita et al., 2024), we used an online collaboration platform and proceeded in two steps. First, participants provided written feedback on the presented target and images via the platform's chat function. Second, we facilitated an open discussion to surface points of agreement, clarify assumptions, and identify contested elements. The chat round yielded **37 discrete comments**, which form our primary data source, including questions and comments such as *"What particular aspects within circularity can digitalization enhance?"* and *"[I] would see digitalization as one enabler out of several ones." Such* real-time input and dialogue align with established practices for participant engagement in backcasting-oriented scenario design (Höjer et al., 2011; Quist et al., 2011). During the discussion, we explicitly invited the experts to validate and, where appropriate, challenge the target and future images, with particular attention to the connective role of digital technologies. In line with prior work, the exchange balanced visionary exploration with feasibility considerations (Vergragt & Quist, 2011). Immediately after the workshop, the author team consolidated the workshop output through a structured synthesis based on the chat transcripts and contemporaneous discussion notes; the discussion itself was not audio-recorded.

The workshop feedback prompted three substantive revisions of our initial images of the future. First, rather than portraying digital technologies merely as enablers, the scenarios now position them as the structural backbone that binds CE principles to day-to-day operations. Second, secure, interoperable data sharing emerged as the non-negotiable foundation for circularity, without which no other technological intervention scales. Third, the workshop highlighted the need to detail complementary shifts in governance, incentives, and workforce capabilities that must co-evolve with technological deployments.

Scenario construction via the Golden Circle. We translated the enriched material into two more granular scenarios using Simon Sinek's (2009) Golden Circle framework as an organizing lens – *why, how,* and *what* – thereby ensuring vertical coherence from purpose to practice. For each scenario, the *why* clarifies the normative anchor (e.g., carbon neutrality, closed-loop systems, resource efficiency), the *how* specifies a technology portfolio (e.g., IoT, digital product passes, data spaces), and the *what* describes concrete CE practices, business processes, and actor collaborations. This structure has two advantages: first, it guards against techno-centrism by tying digital solutions to societal goals; second, it renders the pathways relatable for practitioners, who often demand a clear linkage between high-level aspirations and operational levers. Together, the two images of 2050 articulate what success might entail for a digitally enabled circular automotive industry.

Step 4: Pathway Development. In the final step, we move from "vision" to "navigation" by deriving time-phased transition pathways required to traverse the gap between today's baseline (Step 2) and the aspirational futures (Step 3). Mirroring the creative rhythm established in Step 3, we began with a series of iterative author-team sessions that combined visualization techniques and memoing to draft an initial transition pathway. This internal work surfaced candidate sequences of technological advancements, policy levers, and organizational shifts, and crucially, exposed tensions between long-term ambition and near-term feasibility.

To subject these preliminary sequences to external validation, we conducted another one-hour workshop in late August 2024 that included experienced practitioners from the automotive industry. The online format again employed an online collaboration platform for synchronous annotation and commentary, enabling participants to critique our draft in real time and to foreground implementation risks that might otherwise not have surfaced. Feedback converged on the need to disentangle foundational capacity-building from early rollout activities; accordingly, the pathway was restructured from three to four sequential phases, each marked by a distinct objective yet tightly coupled through staged policy incentives and agile governance mechanisms.

Table 3 summarizes the workshop composition from Steps 3 and 4, including participants' professional backgrounds, roles, and years of experience, providing transparency into the diversity of expertise consulted. An overview of the consolidated changes to the target definition, images of the future, and pathways resulting from the workshops in steps 3 and 4 is provided in Table A4 in the Appendix.

Table 3. Overview of Workshop Participants

Workshop for step	Topic expertise	Background	Experience
3	Digital Service Innovation & Applied AI in Services	Business, Research	30 years
3	Human-Centered AI & Machine Learning	Development, Research	4 years
3	Human-AI Collaboration & Applied Machine Learning	Development, Research	4 yeras
3	Multimodality & AI-driven Services	Development, Research	6 years
3	Data Sharing & Data Ecosystems	Business, Research	3 years
3	Deep Learning in Computer Science	Development	2 years
3	Service Ecosystems & Data-driven Service Innovation	Research	1 year
3	Human-AI Collaboration & Applied Machine Learning	Research	1 year
3	Human-Computer Interaction & Technical and Human Factors of AI Adoption	Research	1 year
4	Mechanical Engineering for Battery Dissassembly	Development	5 years
4	Mechanical Engineering & Digital Twins	Development	4 years
4	Environmental Planning and Engineering & AI	Development	17 years
4	Mechanical Engineering & Circular Production Planning	Development, Research	3 years
4	Data Sharing & Data Ecosystems	Business, Research	3 years

4 Backcasting the Future of the Automotive Industry

This chapter outlines the results of our four-step backcasting study design to chart a reliable transition towards a circular European automotive industry by 2050. Specifically, Step 1 establishes the normative goal of carbon-neutrality through closed material and production loops enabled by digital technology-driven infrastructures. Step 2 diagnoses the industry's current CE maturity, readiness, and possibilities for digital technology integration. Step 3 constructs two futures that foreground (i) circular design and manufacturing, and (ii) end-of-function value recovery, using EVs as the illustrative artifact in light of digital technologies. Step 4 then backcasts from these futures to outline an actionable transformation pathway for firms, policymakers, and civil-society actors.

4.1 Step 1: Target Definition

Our starting point is the European Green Deal, launched in 2019 as the EU's overarching blueprint for a carbon-neutral and resource-efficient economy (European Commission, 2020). The European Green Deal consists of nine major policy areas, each introducing a set of dedicated regulations, strategies, and funding sources aimed at achieving shared objectives. One of these policy areas is "mobilizing industry for a clean and CE", as concretized in the CEAP.

The CEAP positions itself as "a future-oriented agenda for achieving a cleaner and more competitive Europe" through which "the EU will continue to lead the way to a CE at the global level" (European Commission, 2020, CEAP section 1). The CEAP emphasizes establishing sustainable products as the new standard, while empowering consumers and public buyers to make informed and sustainable decisions, and increasing circularity in production processes by reducing waste and supporting the reuse and recycling of materials. Among others, the CEAP addresses batteries and vehicles as a key product value chain that "requires urgent, comprehensive and coordinated actions" (European Commission, 2020, CEAP section 3) due to their resource intensity and share of carbon emissions.

To operationalize the policy, the CEAP proposes distinct measures to leverage digital technologies: First, it emphasizes the importance of "mobilizing the potential of digitalization of product information, including solutions such as digital passports, tagging and watermarks" (European Commission, 2020, CEAP section 2.1) by establishing "a common European Dataspace for Smart Circular Applications with data on value chains and product information" (European Commission, 2020, CEAP section 2.1). The DPP is envisaged as a key instrument within the CEAP framework, particularly under the Sustainable Products Initiative, to ensure that product-specific data, such as material composition, reparability, and environmental impact, is made digitally accessible across the entire value chain (Voulgaridis et al., 2024). Second, it aims "to ensure that consumers receive trustworthy and relevant information on products at the point of sale, including on their lifespan and the availability of repair services, spare parts and repair manuals" (European Commission, 2020, CEAP section 2.2). Third, it strives to enable greater circularity in industrial production processes by "promoting the use of digital technologies for tracking, tracing and mapping of resources" (European Commission, 2020, CEAP section 2.3). These measures highlight the role of digital technologies in achieving circular objectives, which the EU aims to systematically support and catalyze with respective regulatory instruments.

This action plan, along with other regulatory frameworks at global and national levels, highlights the importance of integrating digital technologies to advance circularity within sectors such as the automotive industry. These initiatives are essential for advancing digital infrastructures that facilitate transparency, traceability, and collaborative decision-making in CE applications, aligning these efforts with strategic sustainability goals. From this strategic alignment between governmental frameworks and digital technologies, we define the following specific target for our further backcasting process:

Achieving a carbon-neutral automotive industry in Europe by 2050 through closed material and production loop systems, aligned with EU policy goals, leveraging digital technologies, data spaces, and DPPs for data collection, integration, and analysis to operationalize circular strategies.

4.2 Step 2: Target Analysis

Having established the normative horizon and its digital underpinnings, this step examines the extent to which today's automotive industry has progressed toward circularity and identifies where critical capability gaps persist, particularly where digital technology integration can bridge them.

4.2.1 CE Principles and Practices

The automotive industry's transition towards circularity is primarily driven by increasing regulation, resource scarcity, and the imperative to reduce environmental harm. Based on expert interviews and the reviewed literature, five interrelated thematic areas emerge as decisive for progress (see Table 4). In the following, we trace how each theme both advances and constrains the transition, thereby laying the groundwork for technological integration.

Table 4. Core Themes and Challenges on Circularity in the Automotive Industry

Thematic category	Technology focus	Key insights	Major challenges
Product-related circularity	Circular Product Design	CE principles must be embedded at vehicle design stage to enable disassembly, repair, and material recovery to minimizing life-cycle impacts.	Strategic disincentives; Misalignment of current designs with CE principles.
	EoL Strategies	Specialized logistics, dismantling infrastructure, and consumer participation to ensure proper battery and component recovery is required for effective EoL strategies.	Insufficient infrastructure and limited investment hinder efficient recovery and reuse.
Systemic enablers	Policy and Regulation	Legal mandates, technical standards, and product traceability are needed to create economic and legal certainty for manufacturers and	Existing regulations are considered vague; lack of standardization and legal guarantees undermines

	consumers alike.	adoption of reused components.
Consumer Perception	Consumer acceptance of remanufactured or reused EV parts remains limited due to concerns about quality, reliability, and residual value. Communication strategies and quality certifications are key to increasing trust.	Negative perceptions of used parts, marginal price differences to new components, and inadequate incentives for reused parts deter uptake.
Economic & Market Dynamics	Disruptive shifts present both risks and opportunities for circularity and require adaptability in product and business strategies.	Uncertainty over future roles, rapid technology evolution, and possible obsolescence of current CE strategies.

Circular Product Design: Design decisions already lock in a considerable amount of a product's lifetime environmental impact. Consequently, design-for-assembly, repairability, and recyclability has become a focal point of recent CE debates (Schöggl et al., 2024). Yet, interviewees noted that prevailing business models still reward sales volume over circular performance: *"[A manufacturer] doesn't really care how easy it is to dismantle the thing afterwards, because they want to sell a new part" (I2)*. Physical space constraints in today's highly integrated vehicles and the lack of clear economic incentives further reduce the viability of prioritizing CE principles (Thompson et al., 2020). In effect, legacy design practices hinder material and value recovery for current and upcoming fleets – an issue repeatedly flagged by experts as *"a major problem" (I6).*

EoL Vehicle Strategies: As the first wave of EVs reaches retirement, sophisticated logistics, dismantling, and recycling infrastructures are urgently required, particularly to handle their battery packs (Thompson et al., 2020). Experts pointed to under-investment in these infrastructures and to the difficulty of securing consumer participation in take-back schemes: *"The customer must […] hand over the battery to a specialist at the end of the vehicle's life" (I7).* This is also emphasized in the literature, which states that without dedicated collection and sorting networks, high-value components cannot be retained in the loop (Baars et al., 2021).

Policy and Regulation: Interviewees converged on the need for binding, granular regulation "*to promote [CE] adoption" (I2).* Without precise targets and standards, actors in the automotive industry are unlikely to bear the financial burden associated with circular practices. In this context, the updated Battery Directive, which sets a target of 65% material recovery by 2025 and 70% by 2030 (McKinsey & Company, 2023), was criticized by several interviewees for its vagueness (I2, I6, I7, I8), as it invites workaround solutions (I2). Respondents therefore called for mandatory module standardization, harmonized battery-health metrics, and legally backed warranty schemes to promote the uptake of remanufactured components over new ones (I7), as only "*a certain level of security in the form of a guarantee can convince customers to purchase such a product" (I1)*. Similarly, the lack of technical standards for assessing battery condition across different manufacturers and usage histories was identified as a barrier to comparability and thus to market acceptance (I7). Absent these measures, firms hesitate to bear the cost of circular initiatives and consumer trust remains fragile.

Consumer Engagement and Perception: Persistent skepticism regarding the quality and reliability of remanufactured or refurbished parts and components constrains demand. As one expert observed, *"customer acceptance is not yet so high that remanufactured parts or products are used." (I2).* This skepticism is rooted mainly in the perception that new vehicles offer superior reliability, modern technology, and higher residual value (I7). Moreover, the narrow price differential between new and remanufactured components, especially batteries, often tips the balance in favor of new purchases: *"If you end up with a vehicle that would somehow only be worth €2,000 - €3,000 […] and the battery would then have to be bought new for €20,000 - €30,000, then it won't work." (I7).* Particularly in leasing contracts, the cost savings from reused components may appear negligible and therefore fail to incentivize customers (I4). Experts emphasized that shifting consumer preferences depend not only on technological standards but also on strategic communication. As one interviewee explained, *"if I tell the customer that it's used and probably already 20 years old, he won't be very enthusiastic. If I describe it as refurbished, it's a bit friendlier." (I4).* Certification schemes, strategic framing ("refurbished" versus "used"), and transparent performance data are thus critical levers for shifting consumer attitudes (Thompson et al., 2020).

Economic and Market Conditions: Experts and literature characterized the industry's macro-environment as highly volatile, shaped by concurrent shifts to connectivity, autonomy, sharing, and electrification (Ketter et al., 2023). Such turbulence opens niches for entrants who may, in one interviewee's words, "*reassemble a car from the inside out, so that you can easily remove the shell and then take off the cabin and everything is so decoupled that you can completely dismantle a car" (I7).* This volatility is also reflected in the uncertainty surrounding future roles within the automotive industry, as it remains unclear whether the OEM, the supplier, or third-party service providers will be responsible for the EoL strategy (I2, I9). At the same time, rapid advances in battery chemistry risk rendering today's battery packs technologically obsolete within one or two product cycles, as one interviewee observed: *"In five years' time, the batteries of today are […] reprocessed, [they] will probably be an outdated technology in terms of the cell or an obsolete technology, at least in terms of performance" (I1).* Shifting design standards – such as voltage requirements – underscore how technological change can quickly render current components obsolete (I8). Alternative powertrains, including hydrogen fuel cells, could further disrupt current trajectories. As one expert puts it, *"perhaps in one or two generations, the electric car may not be the ultimate desired solution" (I8*). Consequently, CE strategies must remain adaptive, balancing present-day investments with the potential value of future technological pathways.

4.2.2 Technological Integration

The barriers identified in the interviews and the literature indicate that digital technologies constitute critical enablers that can translate circular intentions into operational reality, addressing insufficient, insecure, or siloed information flows across the EV lifecycle. Table 5 summarizes the resulting themes, which we cover in what follows.

Table 5. Core Themes and Challenges on Technological Integration in the Automotive Industry

Thematic category	Technology focus	Key insights	Major challenges
Data collection & traceability	IoT sensors, RFID, digital twins	Smart-factory sensors and digital twins capture high-resolution condition data that support design-for-disassembly and remanufacturing loops.	Retrofit costs for legacy fleets, heterogeneous sensor standards, and persistent data-quality/ownership issues.
Data integration & sovereign sharing	DPPs, digital industrial platforms, federated data spaces (Gaia-X/IDS, Catena-X)	Unite fragmented life-cycle data, enforce usage policies, and enable firms' sovereign, cross-company data sharing.	Reluctance to disclose sensitive information, lack of interoperability & common protocols, and complex governance of data-access rights.
Data analysis & decision support	AI, machine learning, big data analytics, decision support	AI & big data analytics enable predictive maintenance and AI-assisted EoL processes, while higher-level digital twins guide decisions from EoL strategy to eco-design.	Real-time latency constraints, sparse or unlabeled data, limited trust in "black-box" outputs, and the high cost of building and maintaining advanced twin/AI models.

Data collection and traceability. Industry 4.0 technologies – smart-factory infrastructure, IoT sensors, RFID, and digital twins – are now used in many shop floors, generating high-resolution production and usage (Rad et al., 2022; Turner et al., 2022). Real-time monitoring allows firms to adapt processes swiftly, curbing waste and improving material efficiency (Duan et al., 2024; Rizvi et al., 2023; Vinuesa et al., 2020). At the product level, digital twins already automate EV-battery disassembly (Strakošová et al., 2024); at the system level, they guide reuse strategies for high-voltage batteries (van Dyk et al., 2024). Interviewees nonetheless warned that traceability depends on disciplined data capture: *"You must agree on the necessary data and distinguish between the data required for disassembly and those desired" (I6).* Over-specified requests risk OEM push-back, while under-specification limits downstream value retention.

To ease this tension, DPPs attach verifiable lifecycle data to each asset, increasing transparency, boosting remanufacturing yields, and shortening recycling times (Berger et al., 2023; Psarommatis et al., 2024). Yet sensitive battery-health metrics remain "*extremely sensitive and only accessible to the* *manufacturer" (I9)*, illustrating how proprietary concerns still prevent full data disclosure (Fassnacht et al., 2023; Khan et al., 2022; Thunyaluck & Valilai, 2024). Digital twins are accurate virtual models of physical assets, processes, or systems for purposes such as simulation, analysis, and monitoring, thereby enhancing asset management throughout their lifecycle (Ives et al., 2024; Mügge et al., 2023).

Data integration and sovereign sharing[4]*.* While traceability tools generate data, value can be created only when data and information flow securely across organizational boundaries (Mügge et al., 2023). Accordingly, the development and adoption of digital industrial platforms and federated data spaces have emerged as promising solutions to orchestrate information flows across product lifecycles among diverse stakeholders (Kristoffersen et al., 2020; Trevisan et al., 2022; Zeiss et al., 2021). By enabling real-time data integration and analysis, these platforms support more informed and agile decision-making, thereby aligning day-to-day operations with overarching CE objectives (Konietzko et al., 2020; Pauli et al., 2021). In particular, data spaces provide a decentralized yet sovereign framework for secure data sharing between firms and regulatory bodies, making them a credible path to overcoming long-standing reluctance to share sensitive information (Fassnacht et al., 2023; Serna-Guerrero et al., 2022).

Here, initiatives such as Gaia-X[5], the International Data Spaces (IDS)[6] project, and the automotive-specific Catena-X[7] offer decentralized architectures that reconcile openness with control by allowing for direct data exchange without relying on a central repository (Hoppe et al., 2023; Otto et al., 2022). By enforcing common ontologies and usage policies, they aim to mitigate interoperability friction (Vogiantzi & Tserpes, 2023; Winkelmann et al., 2024) and meet regulatory requirements, such as the EU Green Deal and the forthcoming EU AI Act (Burden & Stenberg, 2023). Complementary initiatives (e.g., Cofinity-X[8], IEDS[9], and Manufacturing-X[10]) focus on onboarding SMEs, standardizing interfaces, and aligning incentives (Hupperz & Gieß, 2024).

Despite this momentum, adoption remains uneven. High integration costs and unresolved responsibility disputes cause many firms to keep data to themselves (Fassnacht et al., 2023; Hoppe et al., 2024a). One expert anticipated that *"at some point, standardizing [in product design] becomes necessary. […] It becomes more of a [viable] business model then." (I2).* In other words, sovereign sharing will accelerate only when cost-benefit allocations become transparent and when governance frameworks guarantee data owners' control (Berger et al., 2023; Otto et al., 2022).

Data analysis and decision support. Once datasets are collected and shared, advanced analytics and AI transform them into actionable insights (Bag et al., 2021; Baumgartner et al., 2024; Turner et al., 2022). Predictive maintenance algorithms, for example, can minimize downtime and extend component life, directly supporting remanufacturing loops (Bag et al., 2021; Turner et al., 2020). Digital twin simulations can inform design-for-disassembly and design-for-remanufacturing tradeoffs (Rizvi et al., 2023), enabling early-stage interventions that lower industry-wide risks due to reliance on imported raw materials (Pehlken et al., 2024). AI-assisted recycling lines can now automate the sorting, dismantling, and regeneration of EoL EV batteries (Short et al., 2024).

However, technical feasibility does not guarantee adoption. Organizational capabilities such as analytics literacy, cross-functional governance, and top-management commitment are still maturing, leaving a gap between analysis and practical action (Vogiantzi & Tserpes, 2023). Emerging regulation may provide necessary incentives by requiring auditable, high-quality data pipelines, making robust decision support a compliance imperative.

4.3 Step 3: Images of the Future

Building on the 2050 target and the preceding target analysis, this section presents a visionary, yet evidence-anchored portrayal of how the future automotive industry can embody CE principles through advanced digitalization. Rooted in the EU Green Deal and the CEAP, the vision pivots from vehicle-as-a-product to a more service-oriented mobility model, underpinned by a mobility-centric data ecosystem that

[4] We use "sovereign sharing" to denote cross-organizational data sharing in which data providers retain control over access and permitted use (e.g., through enforceable usage policies, purpose limitation, and revocation rights).
[5] https://gaia-x.eu/ (accessed 27/09/2024)
[6] https://internationaldataspaces.org/ (accessed 25/05/2025)
[7] https://catena-x.net/en/ (accessed 25/05/2025)
[8] https://www.cofinity-x.com/ (accessed 25/05/2025)
[9] https://ieds-projekt.de/en/front-page/#News (accessed 25/05/2025)
[10] https://www.plattform-i40.de/IP/Navigation/EN/Manufacturing-X/Manufacturing-X.html (accessed 25/05/2025)

informs decisions across the vehicle lifecycle. Although sustainable mobility and transportation will ultimately include various modes of transportation (e.g., shared, public, and micro-mobility services), we assume that EVs will remain central to both individual users and fleet operators. The goal, therefore, is not to replace the automotive industry but rather to reconfigure it so that carbon neutrality and circular value retention become intrinsic outcomes rather than secondary considerations.

Within this horizon, two interdependent phases emerge: first, *design and manufacturing,* in which modular, upgradable, and resource-efficient EVs are developed and produced through pervasive Industry 4.0 technologies; second, an *end-of-function value recovery* phase that maximizes lifecycle extension via remanufacturing and recycling of high-value components. Taken together, these two images demonstrate why circularity is imperative, how digital infrastructures and data-driven governance can operationalize it, and what concrete practices may materialize in the industry by mid-century. In Sinek's (2009) Golden Circle terms, purpose (why), process (how), and outcome (what) are aligned into a coherent trajectory towards a digitally-enabled circular automotive industry. The concrete manifestations of this trajectory are detailed in the following subsections.

4.3.1 Image 1: Design and Manufacturing

By 2050, the automotive industry designs and builds vehicles making circularity the default outcome rather than an aftermarket correction. From the initial blueprint, engineers work to eliminate waste and pollution, secure ethically sourced materials, and ensure that every component can remain in productive use for as long as possible; these objectives comply with the EU Green Deal, the CEAP, and the battery-specific directives that have steadily tightened since the 2020s. Each traction battery leaves the factory with a DPP – described as the product's "digital DNA" – that records its origins, material composition, recycled content, carbon footprint, and real-time state-of-health data. The passport also stores modelled trade-offs between remanufacturing and outright replacement, so designers, service providers, and regulators can make evidence-based decisions throughout the battery's life. Through this "design for circularity" ethos, manufacturers in 2050 proactively anticipate each EV's full lifecycle from the beginning, ensuring that longevity, upgradability, and EoL recovery are supported to the highest degree possible.

IoT sensors and RFID tags embedded in the battery's cells, modules, and housings – as well as in other critical EV components – capture high-resolution production (e.g., production batches, quality metrics, calibration settings) and usage data (e.g., charging cycles, repair instances, environmental conditions) that feed into multi-scale digital twins. During early design, these digital twins simulate thermal behavior, degradation pathways, and disassembly sequences under various conditions, revealing configurations that maximize durability and facilitate modular replacement. As field data accumulate from assembly onward, the DPP instance is updated, and machine learning routines compare simulated and actual performance, identify emerging failure modes, and push design heuristics back to engineering teams; the result is a rolling, data-driven improvement cycle in which every new model embodies lessons learned from the previous fleet in the field.

Seamless information exchange depends on mature, federated data spaces that connect actors within the automotive ecosystem. By 2050, a European-wide automotive platform combines Catena-X's industry-specific tooling with the interoperability and data sovereignty principles of Gaia-X, and the reference architectures and protocols of the IDSA. Standard ontologies and agreed data schemas ensure that a cell's chemistry or a module's residual capacity means the same thing to every actor. Access rights are enforced through a permissioned distributed ledger layer (e.g., a blockchain) that lets firms retain granular control over proprietary files while exposing lifecycle attributes – carbon intensity, remaining-life indicators, repair histories – to authorized partners. The architecture transforms the passport from an internal record into an ecosystem resource: an OEM designing a next-generation battery can query recyclers' inventories of recovered lithium and cobalt; suppliers upload certification data directly to the passport; repairers and remanufacturers receive read-only access years in advance, allowing them to plan tooling and parts logistics. The governance model of the platform addresses long-standing reluctance to share sensitive data – an interviewee cautioned that "*you must agree on the necessary data and distinguish between the data required for disassembly and those desired*" (I6) – while protecting information that remains, in the words of another respondent, "*extremely sensitive and only accessible to the manufacturer" (I9).*

Once the data is collected and integrated, advanced analytics translate information into action, empowering proactive, adaptable circular practices across design and manufacturing. For example, at early design stages, AI models run counter-factual disassembly scenarios and recommend design changes that raise future material-recovery rates; digital twins calculate the carbon and cost implications of substituting recycled for virgin raw materials; analysis of past failure data informs design rules, ensuring that new components are inherently modular, upgradable, and reusable across future vehicle platforms; predictive algorithms warn production planners when an increase in component obsolescence will require remanufactured modules on short notice. Consequently, assembly lines are configured for high-mix throughput following an adaptive manufacturing paradigm, able to slot certified secondary parts alongside newly manufactured ones without compromising safety or warranty obligations.

In this envisioned 2050 landscape, the *"why"* of resource preservation, material longevity, ethical accountability, as well as data sovereignty is inseparable from the "*how"* of pervasive sensing, interoperable data spaces, and trustworthy analytics. Together, they produce the "*what"* of modular, upgradeable, and transparently documented products while minimizing waste and obsolescence, as well as inefficiencies through adaptive production systems, consolidated in Figure 1. Design and manufacturing thus shift from linear output to orchestrated management of continuous material and information flows, setting the foundation for the extended-life and closed-loop practices described in the subsequent end-of-function value recovery image.

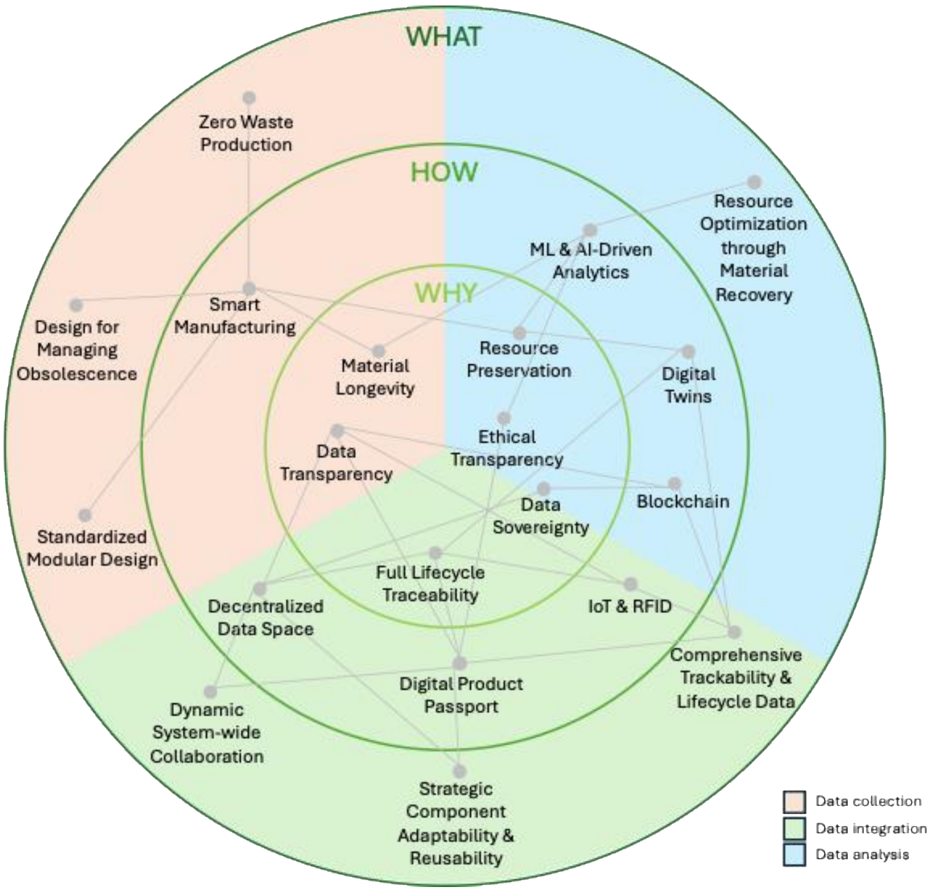

Figure 1. Fundamental Principles (why), Enabling Technologies (how), and Tangible Practices (what) of the Design and Manufacturing Phase in a CE by 2050

4.3.2 Image 2: End-of-Function Value Recovery

By 2050, many first- and second-generation EV fleets will retire without having been designed for circularity, whereas later cohorts will arrive with full lifecycle planning already embedded. The industry's challenge, therefore, is twofold: differentiate between legacy and lifecycle-read vehicles and, for both, capture the maximum residual value of high-value parts – above all, traction batteries – through repair, remanufacture, repurposing, and ultimately recycling. This objective is no longer aspirational but codified in a regulatory regime that extends the 2020s Battery Regulation. Legislation now requires a DPP for every critical component and mandates the recovery of at least 90% of strategic materials, making end-of-function circularity non-negotiable.

A federated digital ecosystem supplies this infrastructure. Throughout the use phase, embedded IoT sensors continuously monitor performance and update the DPP with metrics such as capacity fade, charge-cycle counts, and thermal events. When performance falls below predefined thresholds, the vehicle connectivity system automatically informs the user and flags the battery for end-of-function processing and transmits relevant passport data to authorized actors via the decentralized data space. Secure data sharing protocols ensure that even competitors can view necessary information without compromising proprietary knowledge, while AI-driven analytics rank value-retention options in accordance with the circular hierarchy if repairing the component is not possible or feasible.

First, repurposing is pursued when, for example, batteries retain substantial residual capacity (e.g., below 80% of their original capacity (Iqbal et al., 2023)). Machine learning models, calibrated using the passport's performance history and real-time diagnostic data (e.g., generated by a certified workshop), predict remaining useful life for alternative applications (e.g., stationary energy storage in renewable power grids) and simulate second-life duty cycles using the battery's digital twin. Decentralized data marketplaces match flagged batteries with, for example, stationary-storage buyers that meet safety and documentation requirements, and the passport accompanies the unit into its new role, maintaining traceability across sectors and lifecycles.

Second, remanufacturing targets components that can be reconditioned to like-new condition and reintroduced into the market. On arrival at the remanufacturing hub, robots guided by computer vision and digital twin schematics disassemble the pack, cells undergo automated impedance and capacity testing, and AI classifiers separate modules suitable for reassembly from those destined for closed-loop recycling based on original specifications and current regulatory standards. High-performing cells are re-bundled into certified refurbished modules, which are returned to the market as components for both new EV models and service replacements, with the passport updated to reflect their new status – thereby extending functional life while preserving data provenance.

Third, recycling and material recovery close the loop when other options are no longer viable due to irreparability or technological obsolescence. By 2050, recycling facilities are tightly woven into the digital infrastructure: as soon as AI evaluation consigns cells to recycling, the data space queues them for batch-specific processing. The DPP's granular material breakdown enables real-time adjustment of hydrometallurgical and pyrometallurgical parameters, pushing critical-material recovery rates above 90%. Recovered cobalt, nickel, and lithium are indexed in the data space, allowing battery plants to secure secondary raw materials with verified purity and ethical origin; the passport for each new pack records its recycled content, providing regulators with auditable proof of quota compliance. Consequently, the once-disparate stages of use, disposal, and resource extraction are now merged into a single, data-driven continuum of resource management.

End-of-function value recovery shifts from a terminal event to a strategically governed inflection point. Continuous data capture, sovereign information exchange, and advanced analytics weave use, disassembly, and resource recovery into a closed-loop circular continuum, ensuring that by 2050 automotive materials circulate indefinitely within an information-rich, digitally mediated ecosystem. Figure 2 synthesizes this vision, linking the fundamental "*why*" of CE imperatives with the "*how*" of enabling technologies and the "*what*" of tangible value-retention practices.

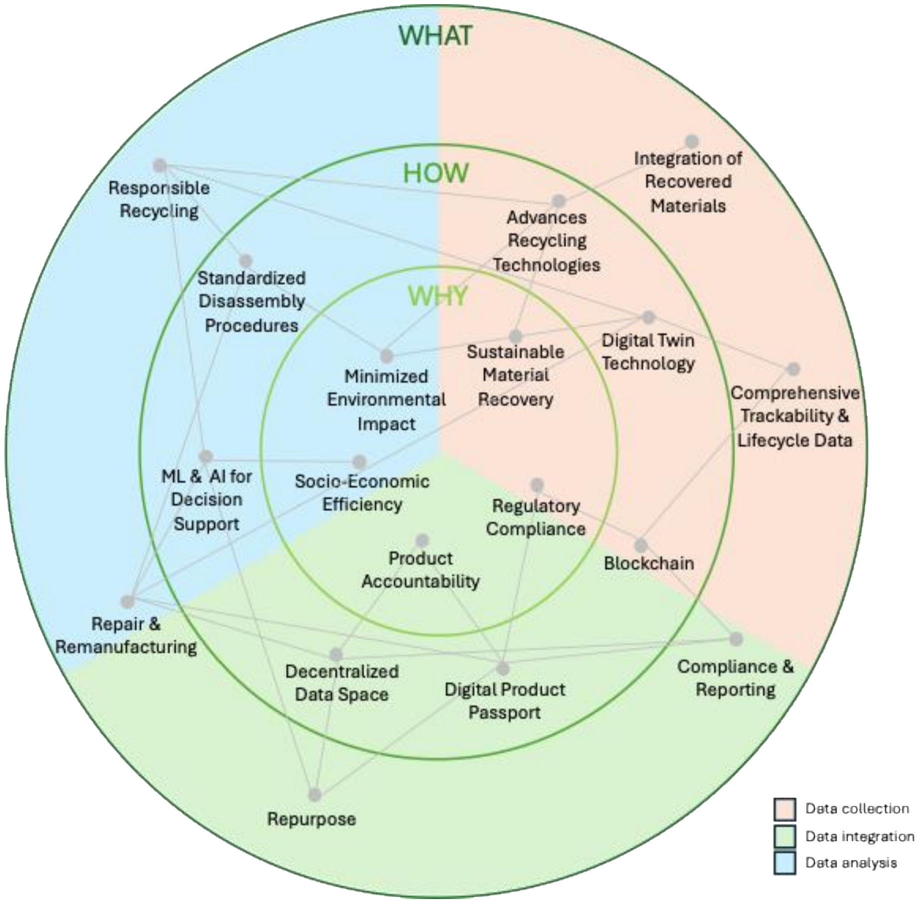

Figure 2. Fundamental Principles (why), Enabling Technologies (how), and Tangible Practices (what) of the End-of-Function Value Recovery Phase in a CE by 2050

4.4 Step 4: Pathway to the Future

Achieving the carbon-neutral, digitally enabled circular vision requires a staged transformation that couples technological diffusion with evolving governance and organizational routines. To illustrate this trajectory, we draw on the *industrial-path transformation* lens of Baumgartinger-Seiringer et al. (2021), which distinguishes three generic transition moments – initiation, acceleration, and consolidation – and foregrounds shifts in actor constellations, guiding visions, and physical asset configurations. Nevertheless, our workshop results reveal that the traditional single acceleration moment here splits into two consecutive phases to capture the empirically observed learning curve and scale-up dynamics in greater detail. We see a comparable rhythm in the automotive industry: as the actor base broadens from an initial regulatory coalition to an ecosystem-wide alliance, coordination practices and shared visions co-evolve, enabling the progressive realization of circularity. The resulting pathway, therefore, unfolds in four successive stages: foundation (1), integration and exploration (2), expansion and scaling (3), and ecosystem maturity (4) – each characterized by a specific mix of actors, coordination practices, and tangible-asset reconfiguration, see Figure 3. Importantly, only stage 1 is associated with a calendar date in Figure 3: the foundation stage can be anchored to concrete regulatory milestones (e.g., the rollout of battery passports in the EU by 2027). The subsequent stages are intentionally presented without fixed dates to avoid false precision, because their timing is sensitive to learning dynamics, adoption trajectories, and the co-evolution of market and regulatory conditions.

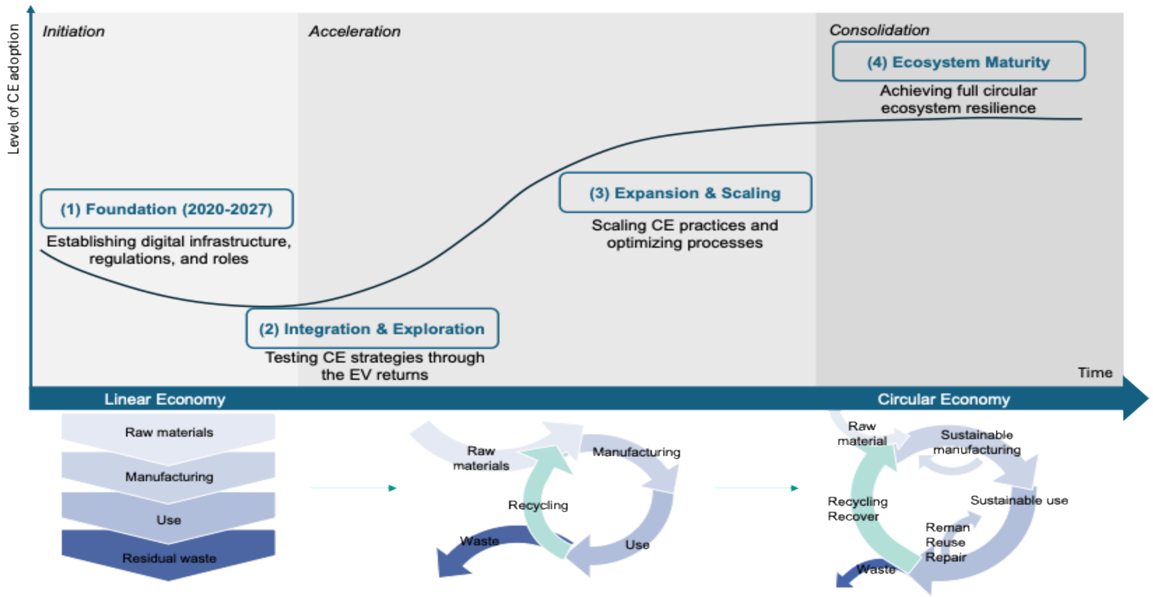

Figure 3. Four-Stage Model of the CE Adoption Curve (Only Stage 1 is Dated; Later Stages are Intentionally Undated to Avoid False Precision)

Momentum intensifies in expansion and scaling, the second half of the *acceleration* moment: shared circular visions solidify, cross-sector alliances proliferate, and asset modification shifts from isolated pilots to systemic upgrades. At this stage, the industry is moving towards more seamless and effective CE practices, exhibiting signs of growth and scaling. The final stage represents the automotive ecosystem's full maturity in CE practices, aligning with the *consolidation* phase. The automotive industry will have developed a robust and resilient CE that can adapt to future challenges. The focus now shifts towards improving efficiency and achieving long-term sustainability, with stakeholders working together to achieve their goals.

The further we look into the future, the greater the uncertainty becomes in our predictions due to learning dynamics, technological and market-driven developments, and regulatory co-evolution. Moreover, our research, particularly the expert interviews, suggests that despite the goal of a CE, raw material extraction seems inevitable for now, and that closer integration with other industries may be necessary to leverage cross-industry synergies. Therefore, we argue that the automotive industry in 2050 will be characterized by feedback loops, where the generation of virgin raw materials and waste is minimized, and synergies with other resource-intensive industries are increased. Below, we introduce the four stages in more detail.

4.4.1 Stage 1: Foundation ("Initiation") (2020-2027)

The foundation stage, which spans roughly from 2020, when the CEAP was released, to 2027, is essential to laying the groundwork for transitioning from a linear to a circular automotive industry. During this period, the focus will be on establishing the digital, regulatory, and infrastructure frameworks required to support CE practices. A key objective is to integrate the necessary infrastructure to identify and collect all relevant data throughout the battery lifecycle, as mandated by the EU Green Deal, primarily by implementing the battery passport for EVs. This battery passport, issued by car manufacturers starting February 2027 as part of the EU Battery Regulation, will lay the foundations for circular design, production, and lifecycle management. This development informs our projection that this stage will last until 2027.

During this period, a robust data infrastructure will need to be established to ensure the timely availability of data for all stakeholders. This data will inform decision-making around CE principles and support the development of new processes that integrate CE practices into the industry. Initial efforts should prioritize incorporating CE principles into design and manufacturing processes to drive the long-term transition from the beginning of the supply chain. Manufacturers, suppliers, and battery manufacturers will need to adapt their processes to emphasize standardization, modularity, reusability, and recyclability. Technologies such as digital twins, blockchain, IoT, and integrated sensors will be crucial in building a data-driven environment. Platforms like data spaces will enable real-time monitoring, traceability, and seamless data sharing across the industry, fostering engagement and collaboration among stakeholders and informed decision-making. Government regulators and policymakers will be instrumental in establishing and enforcing policies that drive the industry's transition to circularity. The expected regular assessment of compliance at this stage will be the primary driver of innovation and transformation.

Challenges such as resistance to new technologies, inconsistent regulatory enforcement, and high upfront costs may arise for industry stakeholders and consumers. Overcoming these challenges will require proactive engagement with all stakeholders along the supply chain, careful planning, and a commitment to continuous improvement. At the end of this stage, the industry must have a solid foundation of digital and regulatory frameworks in place to initiate the next stage of the transition to a circular automotive industry.

4.4.2 Stage 2: Integration & Exploration ("Acceleration I")

The integration and exploration stage will be characterized by embedding and validating CE practices in the rapidly expanding automotive industry. With EVs accounting for 13.6% of new registrations in the EU in 2024 (over 1.4 million vehicles) (European Environment Agency, 2025), and the market share increasing to 16.4% in the EU year-to-date (October 2025) (ACEA, 2025), this phase addresses the sustainability challenges posed by the influx of returning EVs and batteries. Recent research indicates that EV batteries typically last 8-10 years, depending on usage patterns and maintenance, underscoring the need to develop sustainable lifecycle management strategies and effective take-back systems (RecurrentAuto, 2024).

During this period, industry leaders, such as manufacturers, will focus on redesigning batteries for circularity, integrating CE principles into lifecycle management, and establishing take-back systems. The increase in returned batteries will enable significant improvements to be analyzed and incorporated into the battery redesigns. This stage will also focus on using data to improve decision-making throughout the product lifecycle, from reduce to reuse and recycling. Advanced technologies, such as IoT and AI, will enable real-time data collection and predictive analytics, thereby improving resource efficiency and lifecycle management. Implementing industry-wide data spaces or similar infrastructures can standardize data sharing, enabling all stakeholders across the value chain to collaborate and make informed, data-driven decisions supported by predictive analytics.

However, this stage will also face uncertainties, including variability in technology adoption rates and potential supply chain disruptions as new CE practices and methods are introduced. Technological advancements in battery chemistry and design are anticipated (Precedence Research, 2024) and may render current remanufacturing methods obsolete, requiring continuous adaptation to maintain sustainable practices. To address these challenges, the industry must prioritize collaboration and clear communication and demonstrate the tangible benefits of CE practices to the stakeholders.

4.4.3 Stage 3: Expansion & Scaling ("Acceleration II")

After integration and exploration, the automotive industry will focus on expanding and refining the digital and circular frameworks established in earlier phases. With the foundational infrastructure now in place, the industry will expand CE practices across the value chain, embedding advanced digital technologies, such as AI, blockchain, and IoT, throughout the lifecycle – from raw material sourcing to end-of-function value recovery. These technologies will facilitate seamless data flow and enable real-time decision-making, allowing the industry to dynamically adapt to changes in material availability, market demand, and regulations.

A key focus will be refining vehicle-wide DPPs and advancing digital infrastructure. These tools will enable predictive lifecycle management, allowing manufacturers to anticipate component wear and failure, thereby improving reuse and recycling processes. The industry is expected to continue advancing AI-driven decision-support systems, focusing on predictive lifecycle management of components based on real-time data, particularly to predict better when EVs are likely to return for end-of-function value recovery processes. With more accurate forecasts, companies can scale their remanufacturing and recycling systems and streamline the return of viable components to the manufacturing process. This approach will ensure that materials are directed to their most sustainable use, particularly in decision-making processes for circular strategies. Governments and international bodies will likely play a key role in aligning regulations with the advanced state of CE practices. During this period, there may be a push for standardization in component interoperability, material sourcing, and recycling practices to reduce the risk of regulatory fragmentation and ensure that CE strategies are implemented consistently across regions and markets. Regulatory compliance is expected to be increasingly tied to incentives, such as tax breaks or subsidies, for companies that excel in CE practices and carbon neutrality, or penalties for those that do not, potentially driving further innovation and broader adoption.

As circularity gains traction in the industry, consumer behavior and market dynamics may shift, although regulatory mandates could reduce the burden on individual consumers by institutionalizing CE practices upstream. Consumers and partner companies may demand greater transparency about the environmental and social impacts of their purchases, leading companies to adopt more open business models. This transparency could enable interested consumer segments and ecosystem partners to track the lifecycle of vehicles and components, from raw material sourcing to end-of-function value recovery, thereby supporting demand for sustainable products where sustainability attributes are salient. The secondary market for EV components is expected to grow as advances in remanufacturing and repurposing create new business opportunities. However, this stage will be characterized by the rapid pace of technological innovation, which may outpace the industry's ability to adapt without significant disruptions. Additionally, concerns about data security and privacy will be debated as data sharing and traceability expand across the value chain and will need to be addressed along with robust cybersecurity strategies. Ultimately, resource scarcity will likely continue to be a significant concern, particularly for critical minerals such as lithium and cobalt. As recycling technologies improve, the industry will need to keep pace with material demand to avoid supply chain bottlenecks.

4.4.4 Stage 4: Ecosystem Maturity ("Consolidation")

A late-stage consolidation of the transition toward a carbon-neutral automotive industry by 2050 will focus on deepening circularity and strengthening ecosystem maturity in ways that enhance sustainability, resilience, and adaptability. By then, the automotive industry should be on a clear path toward circularity, with closed-loop systems largely operational and institutionally embedded, as described in the images of the future. This stage is expected to emphasize optimizing for circularity across the automotive lifecycle, including design, manufacturing, and end-of-function value recovery. Efforts to achieve zero-waste manufacturing and disassembly should prioritize the use of recycled materials and the recycling or repurposing of all materials, thereby significantly reducing reliance on virgin material extraction. Product design should further evolve toward standardization to support modularity, ease disassembly, and improve material recovery at end-of-function. Cross-sector collaboration remains critical for developing synergistic solutions that enhance resource efficiency and mitigate environmental impact, particularly at the intersection of mobility, energy, and electronics. For example, repurposing EV batteries for stationary energy storage could significantly contribute to decarbonizing the energy grid, complemented by vehicle-to-grid approaches. Importantly, this stage is not conceived as a definitive endpoint but as an interim stabilization that remains dynamic and revisable: CE "maturity" may continue to shift as technologies evolve, regulatory ambitions tighten, and societal expectations change beyond 2050, potentially through punctuated phases of reconfiguration rather than linear progress.

As circular practices consolidate, digital governance frameworks are expected to be widely established, enabling secure and sovereign data sharing across the value chain; supporting continuous optimization of material flows, energy use, and manufacturing processes; and enabling ongoing compliance with evolving environmental standards. At this point, policymakers are also expected to further harmonize regulatory frameworks and incentive structures, including beyond European borders, to support circular practices while accounting for regionally differing infrastructures and social priorities. By 2050, the automotive industry may thus approximate a circular, digitally enabled, and carbon-neutral configuration that serves as a reference point for sustainability. The successful realization of the formulated target will depend on the industry's capacity to navigate the interplay of technology, policy, market dynamics, environmental challenges, and uncertainties, and to sustain learning and adaptation as conditions continue to change.

5 Discussion and Conclusion

Using a backcasting methodology, this study envisioned how the European automotive industry might operate within a CE by 2050 and traced the socio-technical pathway required to reach that horizon. The findings demonstrate that information – captured through DPPs, exchanged via sovereign data spaces, and converted into intelligence by advanced analytics – is the decisive resource to bind design, manufacturing, use, and end-of-function practices into a single, value-retention continuum. By integrating digital technologies with stringent but predictable regulation, the industry can transform linear value chains into adaptive circular ecosystems.

5.1 Implications for Research, Practice, and Policymaking

Theoretical implications. For the IS community, the study makes three interrelated contributions. First, it contributes to the emerging body of literature on digital circularity (Agrawal et al., 2023; Saidani, 2024; Voulgaridis et al., 2024) by providing an integrative framework that connects data readiness – including collection, integration, and analysis – to CE strategies throughout the entire product lifecycle. Previous studies often treat digital artifacts, such as passports, twins, or data spaces, in isolation (Ali et al., 2025; Hoppe et al., 2023; Langley et al., 2023). However, by embedding these artifacts within a staged transformation model, the study demonstrates that their capabilities are cumulative and path dependent. For example, sensors generate traceability only if interoperable standards exist, standards generate value only if analytics translate raw data into actionable information, and analytics yield circular outcomes only if governance routines allocate responsibilities and rights along the chain. This layered perspective elaborates on the infrastructuring view of IS (Eaton et al., 2015; Pipek & Wulf, 2009), positioning digital technologies as "boundary resources" that co-evolve with regulatory scripts, market logics, and material artifacts.

Second, the work enriches sociotechnical transition theory (Besson & Rowe, 2012; Lyytinen & Newman, 2008; Poutanen, 2021) by demonstrating how digital infrastructures influence the pace of industrial change. The four-stage pathway adapts the industrial-path transformation lens of Baumgartinger-Seiringer et al. (2021) and shows that acceleration splits into two sub-phases: an explorative learning sub-phase dominated by interpretive alignment and standard refinement, and a scaling sub-phase driven by capital investment once uncertainty falls below a threshold. Digital technologies play different roles in each phase. In the exploration phase, digital technologies can be interpreted as epistemic objects that help stabilize shared visions, whereas in the scaling phase, they primarily function as coordination devices that automate compliance and lower transaction costs (Star & Griesemer, 1989). This finding sharpens our understanding of *when* and *why* actors commit to the transition by showing how digital technologies shift from supporting shared learning to enabling scaled coordination.

Third, the scenarios promote design science research on sustainable IS by contributing to what Gregor and Hevner (2013) refer to as mid-range design theory. The images of 2050 can be interpreted as prescriptive and plausible blueprints that connect context-specific artifact instantiations with high-level principles, such as the waste hierarchy. Across the scenarios, recurring requirements emerge, such as traceability, sovereignty, and real-time analytics, which can be synthesized as higher-level design requirements and mapped to eventual design features, including unique identifiers, policy-controlled interfaces, and hybrid AI models. This mapping provides a transferable design knowledge base that future artifact builders can test, refine, or repurpose in automotive or other resource-intensive domains. To avoid fragmentation, scholars should coordinate their efforts around a shared future vision such as the one articulated here, thereby advancing a coherent program of sustainability-oriented digital innovation.

Practical implications. For automotive practitioners, the analysis clearly articulates that the path to circularity begins long before the first component leaves the factory. Robust collaboration among designers, suppliers, logistics providers, and EoL processors is essential because each party manages a different part of the EV's information trail. By implementing (1) data collection via DPPs and IoT sensors that capture product histories and material attributes, (2) data integration through interoperable data spaces that ensure secure and sovereign data sharing, and (3) data analysis via advanced AI systems that generate actionable insights) as complementary layers, firms can determine in real time which option – repair, refurbish, remanufacture, or recycling – best captures residual value. Together, these data-driven decision layers transform environmental compliance into a source of operational and economic value. Transitioning from product-centric to service-centric business models, such as leasing, battery-as-a-service, and vehicle-to-grid integration, further aligns profitability with component longevity and modularity and can create opportunities for differentiation through circular services and verified product sustainability data.

Policymakers can accelerate the transition by combining hard mandates with soft incentives. Binding policies that mandate the use of digital technologies for traceability and sustainability, such as the upcoming battery passport in 2027, and interoperable interface protocols, establish legal certainty and prevent free-riding. Building on our study, legislating standardized DPPs across the industry is essential to maintain consistency in how product materials and EoL treatment is documented. Meanwhile, subsidies for research and implementation projects, as well as tax credits for, e.g., smart factory retrofits, reduce the risk of adoption. Since passport data will span multiple lifecycles, regulators should establish audit mechanisms that verify data quality without compromising the security of intellectual property. Piloting sandbox environments for data space governance, for example, can help identify liability gaps and refine enforcement toolkits before full-scale rollouts. This comprehensive policy approach will equip all key stakeholders to actively participate in and benefit from the transition to a sustainable automotive industry.

Information systems as adaptive infrastructure. Across these domains, IS emerge as adaptive infrastructures that shape and are shaped by evolving patterns of interaction. As user roles shift from ownership to stewardship and trust requirements evolve from bilateral contracts to ecosystem governance, IS must support transparency, explainability, and dynamic permissioning. Research based on socio-technical systems theory (e.g., Bostrom and Heinen (1977)) can explain how these evolving roles affect power, knowledge, and control, thereby influencing the design and institutional embedding of digital infrastructures.

By situating IS at the intersection of political ambition, technological feasibility, and industrial practice, this study highlights their mediating role in translating macro-level sustainability objectives into micro-level operational decisions. In doing so, IS render circularity a practical reality for complex, data-intensive sectors, such as the automotive industry, and provide fertile ground for future theory building at the confluence of digital transformation and ecological transition.

5.2 Limitations & Future Research

We acknowledge several limitations to our research, including its reliance on the existing knowledge on current technologies, which may impact the feasibility of the proposed pathway. As a concrete, regulation-aligned interim benchmark, the EU Batteries Regulation (EU Regulation - 2023/1542) mandates that by 2031 traction and industrial batteries must contain at least 16% cobalt, 6% lithium, and 6% nickel from certified secondary (recycled) sources, rising to 26%, 12%, and 15% respectively by 2036 – targets that far exceed today's sub-5% recycled share. Despite expectations of continuous technological progress, the industry faces many uncertainties in how the transition to a CE will unfold both on national and global levels. Moreover, the industry must stay alert and adaptable to both ongoing and potential future disruptions. Developments related to climate change, geopolitical tensions, or rapid technological advancements pose significant risks to the stability and predictability of circular ecosystems. For instance, an exacerbation in resource scarcity could affect the availability and cost of critical raw materials for automotive manufacturing. Geopolitical instability might disrupt supply chains, influencing the global distribution of materials and products. Additionally, while unexpected technological innovations could offer potential benefits, they also risk disrupting existing CE strategies. New materials or technologies could render current processes obsolete or necessitate the rapid adaptation of existing digital infrastructures. To navigate these complexities, the industry needs to cultivate a culture of continuous innovation, flexibility, and adaptability, ensuring the resilience of its shift towards circularity and its ability to dynamically adapt to changing economic, environmental, and technological landscapes.

While this study highlights the enabling role of DPPs and data spaces in supporting AI-driven decision-support systems, it does not yet consider how these systems can dynamically respond to changing conditions within a circular ecosystem. There is limited understanding of how other digital technologies can be designed to operate in real-time. Future research should explore how AI-driven systems can be trained to optimize sustainability metrics, such as carbon reduction or material efficiency, in addition to economic metrics. Techniques for handling concept drift in adaptive AI models, where the statistical properties of target variables change over time, should be integrated to maintain the accuracy and relevance of AI predictions (Baier et al., 2019).

Collaboration is widely recognized as a critical enabler for circular ecosystems. This study does not fully address the unresolved tension between data transparency and data privacy in cross-organizational settings. IS research has long emphasized the role of socio-technical system design in facilitating secure and trusted data exchange (Bostrom and Heinen, 1977). However, the practical implementation of data-sharing platforms that ensure both interoperability and proprietary control remains a significant challenge. Future research in IS must focus on developing platforms that encourage cross-stakeholder collaboration without compromising the competitive advantages of individual firms.

While the backcasting approach applied in this study offers a structured means to envision and plan for a circular and carbon-neutral automotive industry by 2050, several methodological limitations should be noted. First, the ultimate goal formulated – though informed by literature and expert input – remains only partially quantified. Future research should aim to define this goal using more specific, measurable criteria to enhance strategic clarity and operational feasibility. Second, the current model lacks integrated processes for ongoing monitoring and dynamic adjustment of the backcasting pathways. This limits the model's responsiveness to unexpected socio-technical developments or emerging constraints. Developing adaptive mechanisms for systematically reviewing progress and modifying both the pathways and the overarching vision could significantly enhance the robustness and usability of the approach.

Future research directions include investigating the socio-economic impacts of transitioning to a CE model within the automotive industry, with a particular focus on labor markets and employment. While CE initiatives often focus on technological and ecological aspects, the success of such transitions ultimately depends on the inclusion, upskilling, and active engagement of the people working within these evolving systems. Examining consumer behavior and acceptance of CE practices, vital for the successful implementation of these models, is also suggested. Additionally, assessing the scalability of the proposed digital technologies and CE practices across other resource-intensive industries is recommended to determine their broader applicability and impact.

In conclusion, we envision the European automotive industry at the forefront of sustainability and resource efficiency by 2050, marking a significant paradigm shift towards a resilient and innovative industry. This transformation extends beyond the adoption of new technologies; it involves the strategic integration of circular processes from the beginning of the supply chain, thereby extending the product lifecycle through innovative end-of-function strategies. As digital technologies become deeply integrated into industrial processes, particularly in DPPs and data spaces, the automotive industry is poised to establish global benchmarks for CE practices, paving the way for a sustainable industrial future that balances economic growth with environmental objectives. Moreover, through active collaboration across all levels of the supply chain and with stakeholders, the automotive industry will not only implement CE principles but also serve as an example for other sectors to adopt these sustainable practices. Crucially, it is the integrative power of IS – linking data collection, secure sharing, and AI-driven insight – that turns this vision into an actionable, scalable reality, underscoring the central role of IS research and practice in achieving a low-carbon industrial future.

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Declaration of AI

During the preparation of this work, the authors used DeepL Write, Grammarly, and ChatGPT in order to revise the grammar, wording, and structure. Multiple versions of ChatGPT over different time periods were used, with all versions using the underlying GPT-4 and GPT-5 Large Language Model. Connected Papers helped visualize the network of academic literature relevant to our topics. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix

Table A1. Overview of Data Sources Applied in Each Backcasting Step

	Backcasting step	Source of data	Type of data	Use in analysis	Focus	Timing
1	Target Definition	Regulatory frameworks such as the European Green Deal and CEAP		Defines the target of achieving a carbon-neutral automotive industry by 2050 through circular strategies and digital technologies.		
2	Target Analysis	Qualitative interviews	14 semi-structured interviews with key stakeholders (suppliers, OEMs, remanufacturers) from 8 organizations	Gathers insights on circularity, current practices, and barriers to integrating digital technologies for circular practices.	Focus on industry-wide circularity and digital technology integration	March 2023 (2 rounds)
		Exploratory literature review	Academic research articles from Web of Science and SCOPUS	Identifies current trends and practices in CE and digital technologies in the automotive industry. Provides foundational knowledge for further research.	Keyword analysis on “circular economy,” “automotive industry,” “digital technologies”	June – August 2024
			Practice-based publications (industry reports, association papers, consultant insights)	Offers practical insights on challenges and practices in the industry, complementing academic research.		
3	Images of the Future	Workshop 1: researchers & IS experts	1-hour participatory workshop	Validates future images and assesses their feasibility regarding the integration of digital technologies for circularity.	Focus on future scenario validation.	August 2024
4	Pathway Development	Workshop 2: automotive industry experts	1-hour participatory workshop	Validates pathways and ensures the practicality of steps necessary to achieve the desired future state.	Focus on actionable pathways and policy alignment.	August 2024

Table A2. Final Literature Sample

#	Title	Authors (Year)	Source	DOI
1	Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies	Rad et al. (2022)	Industrial Marketing Management	https://doi.org/10.1016/j.indmarman.2022.04.012
2	A digital maintenance practice framework for circular production of automotive parts	Turner et al. (2020)	IFAC-PapersOnLine	https://doi.org/10.1016/j.ifacol.2020.11.004
3	Identification of the benefits from the use of Digital Product Passport in a value chain and single organizations	Psarommatis et al. (2024)	IFAC-PapersOnLine	https://doi.org/10.1016/j.ifacol.2024.09.199
4	Factors of digital product passport adoption to enable circular information flows along the battery value chain	Berger et al. (2023a)	Procedia CIRP	https://doi.org/10.1016/j.procir.2023.04.014
5	Confidentiality-preserving data exchange to enable sustainable product management via digital product passports - a conceptualization	Berger et al. (2023b)	Procedia CIRP	https://doi.org/10.1016/j.procir.2023.04.009
6	Recycling Perspectives of Circular Business Models: A Review	Islam et al. (2022)	Recycling	https://doi.org/10.3390/recycling7050079
7	Product Digital Twin Supporting End-of-life Phase of Electric Vehicle Batteries Utilizing Product–Process–Resource Asset Network	Strakošová et al. (2024)	IEEE International Conference on Industrial Informatics (INDIN)	https://doi.org/10.1109/INDIN58382.2024.10774436
8	Integrating Digital Product Passports in Multi-Level Supply Chain for enabling Horizontal and Vertical Integration in the Circular Economy	Thunyaluck & Valilai (2024)	IEEE International Conference on Industrial Engineering and Engineering Management	https://doi.org/10.1109/IEEM62345.2024.10857137
9	A Digital Twin System to Support Decision Making for the Circular Economy	van Dyk et al. (2024)	Studies in Computational Intelligence	https://doi.org/10.1007/978-3-031-53445-4_30
10	Blockchain and Nested Tokens for Tracking, Reusing, and Recycling Batteries	Perez et al. (2023)	Conference Proceedings - 2023 IEEE Asia Meeting on Environment and Electrical Engineering, EEE-AM 2023	https://doi.org/10.1109/EEE-AM58328.2023.10395342
11	Digital Twins: Enhancing Circular Economy through Digital Tools	Pehlken et al. (2024)	Procedia CIRP	https://doi.org/10.1016/j.procir.2024.01.082
12	Conceptualization of a digital product passport to enable circular and sustainable automotive value chains - The combustion engine use case	Pohlmann et al. (2024)	Procedia CIRP	https://doi.org/10.1016/j.procir.2024.01.025
13	Technologies for EoL EV Batteries Recycling: Assessment and Proposals	Short et al. (2024)	ICAC 2024 - 29th International Conference on Automation and Computing	https://doi.org/10.1109/icac61394.2024.10718759

14	Implications of the AI Act in relation to mobility	Burden & Stenberg (2023)	Transportation Research Procedia	https://doi.org/10.1016/j.trpro.2023.11.660
15	Digital Technologies for Sustainable Product Management in the Circular Economy	Baumgartner et al. (2024)	Palgrave Studies in Digital Business and Enabling Technologies	https://doi.org/10.1007/978-3-031-61749-2_7
16	End-of-life decision support to enable circular economy in the automotive industry based on digital twin data	Mügge et al. (2023)	Procedia CIRP	https://doi.org/10.1016/j.procir.2023.03.150
17	Circular economy can mitigate rising mining demand from global vehicle electrification	Duan et al. (2024)	Resources, Conservation & Recycling	https://doi.org/10.1016/j.resconrec.2024.107748
18	The importance of design in lithium ion battery recycling – a critical review	Thompson et al. (2020)	Green Chemistry	https://doi.org/10.1039/D0GC02745F
19	The role of artificial intelligence in achieving the Sustainable Development Goals	Vinuesa et al. (2020)	Nature Communications	https://doi.org/10.1038/s41467-019-14108-y

Table A3. Final Industry Reports Sample

#	Title	Authors/ Organisation (Year)	Source type	URL
1	The zero-carbon car: How circular materials help the automotive industry reach their climate targets	World Climate Foundation (2021)	White paper	https://www.worldclimatefoundation.org/post/building-the-zero-carbon-car
2	Battery recycling takes the driver's seat	McKinsey & Company (2023)	McKinsey Insights report	https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-recycling-takes-the-drivers-seat
3	From waste to value: The potential for battery recycling in Europe	Transport & Environment (2024)	NGO position paper	https://www.transportenvironment.org/articles/from-waste-to-value-the-potential-for-battery-recycling-in-europe
4	Altfahrzeugverwertung und Fahrzeugverbleib 2021	Umweltbundesamt (2024)	Government report	https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/altfahrzeugverwertung-fahrzeugverbleib#altfahrzeuge-2021-niedrigste-anzahl-seit-beginn-der-aufzeichnungen-in-2004
5	Jahresberichte über die Altfahrzeug-Verwertungsquoten in Deutschland 2018–2022	BMUV / BMUKN (2022)	Government report	https://www.bundesumweltministerium.de/download/jahresberichte-ueber-die-altfahrzeug-verwertungsquoten-in-deutschland
6	Global EV Outlook 2024	International Energy Agency (2024)	IEA flagship report	https://www.iea.org/reports/global-ev-outlook-2024

7	Electric Vehicle Market Size, Share and Trends 2025 to 2034	Precedence Research (2024)	Market-analysis report	https://www.precedenceresearch.com/electric-vehicle-market
8	Circular Economy Action Plan (CEAP)	European Commission (2020)	EU policy communication	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN

Table A4. Consolidated Changes to the Target Definition, Images of the Future, and Pathways Resulting from Workshops for Step 3 and 4

Workshop	Target definition	Images of the future	Pathways
1	Refined and contextualized target: from "Achieving a carbon-neutral automotive industry by 2050 through closed-loop systems, sustainable practices and circular strategies" to "Achieving a carbon-neutral automotive industry in Europe by 2050 through closed material and production loops aligned with EU policy goals, enabled by digital technologies, data spaces and digital product passports (DPPs) for data collection, integration and analysis."	- Merged overlapping images "Design" and "Monitoring" into one consolidated image "Design & Manufacturing". - Renamed "EoL Management" to "End-of-Function Value Recovery". - Introduced a "Golden Circle" framing that links purpose, process and practice, integrating circular principles with technology enablers to unfold circular practices. - Updated and refined circular economy practices and enabling technologies to match the new framing.	*Not covered in Workshop 1*
2	Validated the target definition agreed in Workshop 1. *No further edits required*	- Added emphasis on smart manufacturing and active waste-reduction analytics. - Re-focused material efficiency on reusing and re-introducing materials already in the loop. - Called for a high share of standardized parts once technologies reach maturity. - Added automated disassembly and detailed dismantling instruction data as key enablers. - Decisions should prioritize circular economy goals over short-term economic gains. - Included on the technological integration layer decision-support systems and consideration of market, economic and regulatory factors.	- Split the former "Transition Stage" into two distinct stages: "Integration & Exploration" and "Expansion & Scaling". - Removed calendar years from stage labels to present the pathway as an adaptive journey rather than a fixed timeline. - Adapted the visualization to highlight that even at full maturity some residual waste streams will persist. - Noted that pathways serve as guidance but require continuous updates as industry conditions evolve.

About the Authors

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