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# ADOPTING A SUSTAINABLE ENERGY SYSTEM THROUGH THE IMPLEMENTATION OF A CIRCULAR ECONOMY IN THE GERMAN ENERGY TRANSITION

## Circularity in the German Battery Industry – A Case Study of Circu Li-ion

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# Abstract: Work Project

Germany aims to be climate neutral by 2045 and is targeting the transition of its energy system to ensure access to affordable, reliable, and sustainable energy. However, various challenges jeopardize the sustainability of the energy system in the long term. This study holistically examines whether and how the circular economy can present a solution to this problem. The research entails a systematic literature review of the integration of the circular economy into the German energy transition and an analysis of practical examples from wind and solar energy, battery storage, energy efficiency, and zero-emission energy trading.

# Abstract: Individual Work

Germany's increasing dependence on lithium-ion batteries for its advancing electrification of the economy, particularly in the mobility sector, is resulting in a lithium over-demand. As sales of electric vehicles rise, Germany will have to deal with increasing amounts of battery waste. Currently, recycling is the predominant technology for treating end-of-life batteries, but it is not sustainable, and there is a need for green solutions to increase recycling rates. This paper analyzes current battery recycling processes, identifies their inefficiencies, and presents a case study of a start-up that offers a solution to these issues.

# Keywords:

Energy Transition, Circular Economy, SDG 7 – Affordable and Clean Energy, SDG 12 – Responsible Consumption and Production, Sustainability, Wind, Solar, Battery, Energy Efficiency, Emission-Free Energy Trade, Germany

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| | |
|---|---|
| ET | Energy Transition |
| CE | Circular Economy |
| CET | Clean Energy Technologies |
| CRM | Critical Raw Material |
| DII | Desertec Desert Energy |
| EE | Energy Efficiency |
| EoL | End-of-Life |
| EV | Electric Vehicle |
| GHG | Greenhouse Gas |
| LIB | Lithium Batteries |
| MENA | Middle East and North Africa |
| MW | Mega Watt |
| PaaS | Product-as-a-Service |
| PV | Photovoltaic |
| RE | Renewable Energy |
| RQ | Research Question |
| SED | Sustainable Energy Development |
| SLR | Systematic Literature Review |
| SaaS | Solar-as-a-Service |
| SoH | State of Health |
| WE | Wind Energy |

# 1 Introduction

Concerns about climate change dominate many current debates in Germany. Transitioning to low-carbon energy sources has been recognized as a promising step to contribute to fighting climate change and mitigating its damaging environmental impacts. This engagement is aligned to advance sustainable development globally and is addressed by SDG 7, “affordable and clean energy for all” (UN, n.d.-a). The transformation of the energy system can potentially eliminate about half of the carbon dioxide ($CO_2$) emissions currently being released into the atmosphere (Ellen MacArthur, 2022a). Considering today’s challenges, namely the progressive advancement of global warming, the war in Ukraine and resulting energy shortages, as well as reaching the limits of the Earth's capacity, the demand for solutions that drive the transition and can be implemented quickly has risen.

On the one hand, the urgency catalyses the transition; on the other, it may compromise the "thoughtfulness" of the solutions. This scenario entails that the outcomes of decisions necessary in the short-term must not harm and interfere with long-term goals nor lead to new problems in the future. Therefore, the German energy transition (ET) represents a prime example of whole systems change, where politics, economy, and society must collaborate and simultaneously try to manage the transition to renewable energy (RE) and to achieve climate protection targets (KlimaWirtschaft, 2022). In addition to the ET, the concept of circular economy (CE) is referred to as a key strategy for achieving climate neutrality in Germany. 45% of greenhouse gas (GHG) emissions are attributable to everyday products consumed on a take-make-waste approach (Ellen MacArthur, 2022a; KlimaWirtschaft, 2022). Hence, emissions can be reduced tremendously by closing the loop and focusing on extending the lifecycle of resources and physical products.

This study stretches the importance of not looking at the two concepts of the German ET and CE as two separated parts of one solution but integrating both strategies into one another to ensure that no new problems are created along the way. While tackling present-day climate emergencies, it is crucial to “avoid creating an energy infrastructure waste crisis in 20 years” (Heading et al., 2021). The study focuses on the ET in Germany. Due to the early phase-out of nuclear energy and the expansion of renewable energies, the country is considered a pioneer in the ET in the EU. To shape a global sustainable energy policy, Germany needs to be aware of its leadership role and address the integration of a CE into the energy industry to set an example (Steinbacher, 2019).

This study aims to investigate how CE can be integrated into the ET. First, both concepts, including challenges and opportunities, are addressed to provide a scientific understanding of ET and CE. Secondly, the status quo of both concepts is discussed to show discrepancies between the goals and the current reality. Following this, a systematic literature review (SLR) is presented to analyse the integration of CE in ET in a holistic solution, whereas the grounded theory approach is extracted. Finally, to complement the SLR with market research on current evolvements in the German ET, the areas of wind energy, solar energy, battery storage systems, energy efficiency (EE), and emission-free energy trading with the Middle East and North Africa (MENA) is analyzed through the lenses of the degree of compatibility with CE.

# 2 Background to Germany’s Energy Transition and the Circular Economy Framework

This section introduces the ET and CE concepts and their main characteristics. The status quo of their implementation in Germany and their benefits and challenges are then examined in detail to understand possible links and compatibility between the two concepts.

## 2.1 The Energy Transition in Germany

The following section outlines the concept of the Energy Transition (ET) and its underlying ambitions. Although Germany has introduced multiple regulations, the transition still requires an acceleration in expansion toward the shift of renewables and an increase in energy efficiency (EE).

### 2.1.1 Defining Energy Transition

To achieve the ambitious climate targets and to mitigate the impacts of climate change, the transition of the energy system experiences significant advocacy and revolution (F. Dong et al., 2022; UN, n.d.-b). This change is manifested in the European Green Deal that aims for complete decarbonization in the form of zero net emissions by 2050 (European Commission, n.d.-c). The energy transition (ET) targets carbon neutrality and improved energy efficiency (EE) while addressing a shift from fossil-based to low-carbon energy resources, which aims to enable sustainable development and climate resilience (IEA, n.d.; United Nations, n.d.). Per definition, fossil fuels containing coal, oil, and natural gases are considered finite due to their diminishing earthly deposits and the impossibility of store replenishment (National Geographic, n.d.). On the contrary, renewable energy (RE) resources can technically not be exhausted as they are naturally replenished faster than used up (United Nations, n.d.). Therefore, renewables as "zero-carbon" resources hold their designation due to the non-emission of carbon dioxide to the environment (Anjana et al., 2021).

The scope of the ET is not limited to the shift from fossil fuels to RE but also includes the expansion of adequate smart grid infrastructure and the termination of combustion engines toward electric vehicles (EV). These technologies' underlying objective is to decrease further carbon emissions is grounded in a shared goal to increase EE (Eceee, 2019). IRENA (n.d.) states that the ET can achieve 90% of the required energy-related carbon reductions. Ultimately, disruptive transformations to organize the transition must be driven through technological innovation, an adaption of the economy, and governmental regulations (Verbruggen et al., 2010). In Germany, a common consensus on the need for the ET is reached, but a comprehensive, long-term reorganization to “set the course of change so that tomorrow’s energy supply works, its consumption of resources and its impact on the environment is limited to a sustainable level” (Gawel et al., 2014) is needed.

### 2.1.2 Status Quo of Germany’s Energy Transition

This section aims to highlight the discrepancies between climate targets and the status quo, such that the need for timely solutions to further progress in the ET becomes clear.

#### 2.1.2.1 Policy Background

In 2005, the EU set out to plan an energy policy based on the pillars of sustainability, competitiveness, and security of supply (COM, 2006). The Paris Agreement from 2015 bound 196 parties to the shared goal of keeping global warming below two degrees Celsius through reductions in GHG emissions (Hafner and Tagliapietra, n.d.). To achieve this objective, there must be global net-zero GHG emissions by 2050, and all parties have put forward their respective nationally determined contribution strategies. These National Energy and Climate Plans (NECP) show how each country addresses EE, RE, GHG emissions reduction, interconnections, and research and innovation over the next ten years (European Commission, n.d.-b). Germany has set itself the following targets: By 2030, GHG emissions must be reduced by 55% compared to the emission rates in 1990, primary energy consumption must be lowered by 30% compared to 2008, and the share of RE in gross final energy consumption must be increased by 30% (BMWi, 2020). However, it is forecasted that Germany will not achieve its 2030 climate targets on the current path. A recent report by the German Council of Climate Experts states that the continued increase in activity in all sectors without adequate measures to offset the resulting emissions will thwart any progress toward climate goals (Expertenrat für Klimafragen, n.d.). Moreover, the council argues that critical dimensions of ET, such as reducing dependence on fossil fuels in transport, are not progressing at the pace needed to meet government targets.

#### 2.1.2.2 Status Quo of the German Energy Mix

Regarding the energy mix, relevant policies have steadily increased the target share of RE sources since 2000; presently, it aims at 80% of electricity generation by 2050 (BfWK, n.d.). As intermediary goals for 2025 and 2030, shares of 40 – 45% and 65%, respectively, are planned (BMWi, 2020). Germany is on a good track to reach these targets. While conventional sources still represent the dominant share of the energy mix with 56% and 52% in the first and second halves of the year 2022, RE sources contributed 48.5% of total electricity fed in at the end of 2022 (see Appendix A) (Statistisches Bundesamt, 2022). The most common sources of REs are solar, wind, geothermal hydropower, and bioenergy (United Nations, n.d.). In Germany, wind, and photovoltaics (PV) hold the highest shares of the renewable energy mix, followed by biogas and hydropower (see Appendix A). Generally, the current energy mix is being disrupted by various developments in the RE sector. Due to government incentives and higher manufacturing volumes, costs have recently decreased, making renewables more viable options. There has also been a stronger inclusion in political discussions and a shift in mindset toward the need for action against climate change in Germany (IRENA, 2022). The competitiveness of REs can be seen in their costs, with approximately 12-29 ct/kWh and 11-20 ct/kWh for gas and coal, respectively, while the cost of energy generation sat at only 3-11 ct/kWh and 3-8 ct/kWh for PV and wind energy in June 2021 (see Appendix B) (Fraunhofer ISE, 2015).

As energy prices are reaching up to nine-fold values compared with previous years, continued investment into the development of REs remains a critical factor for Germany. However, recent developments in the war in Ukraine and resulting supply constraints have caused the timeline of these plans to be reconsidered. Whereas previousl5y, the remaining active nuclear power plants were to be turned down by the end of 2022, chancellor Scholz has overhauled this decision by extending the running period of three nuclear power plants to April 2023 to deal with the energy crisis (Hauck, 2022; Löschel, 2016). In the same accord, it was decided to keep certain coal plants in the country running longer than planned while holding on to the goal of completing the phaseout by 2038 (Die Bundesregierung, n.d.; Hauck, 2022). Therefore, and as previously addressed, the country remains heavily dependent on foreign fossil fuel supplies; it mainly relies on Russia and the USA for coal and oil imports, while Russia additionally acts as the main exporter of gas for Germany and the rest of Europe (BDEW, 2022). Therefore, energy dependency of Germany requires a rapid rethink, positioning REs as “freedom energies”, according to the German Minister of Finance (Lindner, 2022).

#### 2.1.2.3 Energy Efficiency Standard

The final dimension of interest in Germany's energy transition (ET) progress is energy efficiency (EE). In this scenario, Germany targets to increase EE by reducing primary energy consumption by 30% in 2030 compared to 2008 (BMWi, 2020). However, there has been slow progress in this objective in recent years and small annual fluctuations in primary energy consumption, leaving Germany requiring another 15% reduction in the next eight years (Eckart, 2019; Umweltbundesamt, 2022b). To achieve this, the government has implemented wide-reaching measures in the areas of mobility and transport, agriculture, building efficiency, industry, and trade and services (BMWi, 2020).

Altogether, Germany can demonstrate progress along the various dimensions of the ET – in some more than others, RE expansion is progressing at the required pace to reach the targets. However, the reduction of GHG emissions and increase in EE will require more concerted efforts.

### 2.1.3 Challenges of the Energy Transition

Germany's ET is progressing toward meeting climate goals, but economic and social challenges are emerging (Fischedick, 2013; Kemfert et al., 2015; Pflugmann et al., 2019; Ponitka & Boettner, 2020). Due to their capacity to endanger the achievement of the transition to RE, they are outlined and discussed below.

#### 2.1.3.1 Variability in Energy Supply

The shift to RE sources turns weather-related oscillations into a significant challenge for grid stabilization due to dependency on the environment and the climate. This dependence on the forces of nature ultimately leads to less predictability and high variability in supply output and can result in energy shortages or regional blackouts. Due to the still fossil-dominated energy mix and nuclear power plants, this case has not yet occurred in Germany (Hockenos, 2021). However, to secure this stabilization, the German energy market must match electricity demand to supply rather than the other way around when shifting to REs (MET, 2020).

As the country moves toward a future where more energy is generated from RE sources, more innovative storage solutions, such as energy storage systems or batteries, will be needed to balance supply fluctuations. The market for home storage systems alone (excluding industrial storage) is predicted to grow by 50% from 2020 to 2021 (Figgener et al., 2022). Balancing supply fluctuations will require more communication and anticipation in collaborating with actors and decentralized solutions. Therefore, communication system technologies such as smart grids are another essential component of integrating distributed generation units and RE and anticipating supply and demand accordingly (Yu et al., 2011). However, these technological tools to improve communication between stakeholders and power systems come with data exposure uncomfortable to the average German citizen and at huge investment costs (Giordano et al., 2012).

#### 2.1.3.2 Inadequate Energy Infrastructure

Power supply through RE requires more power plants and systems and a more complex distribution system. Non-RE power plants, 93,454 in number, generate more energy than RE power plants, 138,571 in number, excluding, for example, residential solar, where the number is half as large, creating complexity through the number of operating systems (Bundesnetzagentur, 2022; Destatis, 2022c). While previously, power supply followed a one-directional flow from power plants to consumers, it now travels in both directions as power is generated and used on the consumer side, creating the need for more advanced energy infrastructure. The grid requires a fundamental change as the flow of power in both ways must always be coordinated based on consumption which demands that grids operate smarter to match production and consumption to demand (Energiewende & Assistance Project, 2017; VINCI Group, 2022). Furthermore, most of the energy is generated in the north of Germany, while the energy-intensive industry is in the South. For this reason, electricity must be transported across the country (BMWK, 2020a). To tackle this problem, the German government has already developed a concrete action plan for grid expansion and restructuring processes (BMWi, 2016).

Nevertheless, the implementation of those targets is progressing slowly. Studies demonstrate that 26,000 km of distribution grid expansion is needed until 2050 (Akademie der Wissenschaften Leopoldina, 2020). However, currently, only three tranches are concretely planned, holding a total connection length of 7,656 km (BMWK, 2020b).

Infrastructure challenges apply not only to grid expansion but also to the shortage of skilled workers. Supporting companies in attracting and retaining skilled workers have become an integral part of the government's ET strategy (Kyllmann, 2022b). For example, to install the six million heat pumps planned by the government, 60,000 installers will be needed. For the expansion of solar and wind power generators, the German Institute for Economic Research estimates a lack of around five million skilled workers by 2030, leading to a delay in implementation (Meza, 2022).

#### 2.1.3.3 Critical and Finite Raw Materials

Due to the rollout of RE technologies, the demand for critical raw materials (CRM) for manufacturing has significantly increased. CRM can be defined as minerals and metals whose finite quantity leads to scarcity (European Commission, 2020b; MineralsUK, n.d.). The production, use, and storage of RE sources are highly dependent on CRM (see Appendix C), which can threaten ET's security and speed (Gielen, 2021a; IEA, 2022).

To meet the goals of the Paris Agreement until 2040, the IEA calculates that about 40% of copper and rare earths, up to 70% of nickel and cobalt, and nearly 90% of available lithium of the total demand for materials will need to be used for RE technologies (IEA, 2020). Studies show that RE technologies require a more significant amount of minerals for production than conventional methods. For example, a conventional car needs about 40 kg of raw materials per vehicle, while an electric vehicle (EV) requires about 210 kg of finite resources (IEA, 2020). Clean energy generation also requires much more diverse resources compared to nuclear power than coal and natural gas power generation. For example, wd turbines require 10,000 to 15,000 kg of CRM per MW, while nuclear energy, the fossil source most dependent on CRM, requires only 6,000 kg per MW (IEA, 2020). In addition, the geographical concentration of CRM, also compared to oil and gas, imposes challenges. The two largest producers, the Democratic Republic of Congo and China, cover nearly 70% of supplies, resulting in significant trade dependence. In the process, CRM can become an important bargaining chip for political decisions (Reisch, 2022). Furthermore, the extraction of CRM often does not comply with social and environmental standards as it usually requires high energy and labor, interfering with human rights. Mining often negatively impacts the regions around the mines, resulting in collapses, erosion or pollution of solids, groundwater, surfaces, and the destruction of natural wildlife habitats (KPMG International, 2021).

#### 2.1.3.4 Challenges for Waste Management

The waste generated by retired clean energy infrastructure is related to the increased rollout of REs, which is projected to increase 30-fold over the next ten years (EEA, 2021). Germany currently counts 2.2 million installed PVs and about 28.000 onshore wind turbines (Statisches Bundesamt, n.d.; Statista, n.d.; BWE e.V., n.d.). By the end of 2022, 3,800 wind turbines will reach their end of life in Europe alone. IRENA predicts to have 78 million tons of solar panel waste globally by the end of 2050, including 4.3 million tons in Germany (IRENA, n.d.; Robertson-Fall Tansy, 22 C.E.). However, this calculation neglects the premature termination of these technologies in case of damage or replacement by better and more efficient technologies (EEA, 2021). The profligacy and loss of essential minerals in this process is of concern and was seen in Casper, Wyoming, where ten-thousands of wind turbine blades were buried on a municipal landfill (Martin, 2020).

The problem of waste is not only applicable to renewable technologies but also to the mobility sector as more EVs are entering the market. In 2030, the EU predicts to have 30 million EVs available, resulting in at least 30 million car batteries with a life cycle of around 15 to 20 years (EU Parlament, 2022b). While the recycling process of conventional cars is already matured, the recycling rate of lithium-ions is only 5%. By 2025, the number of lithium-ion batteries reaching the end of their life cycle will have doubled globally from 2021 to 2025 to about 700,000 tons. However, in 2025 only about 400,000 tons of lithium-ion batteries will be available for recycling (Melin, 2018).

#### 2.1.3.5 Policy Failures and the Carbon Lock-In Effect

To enable the ET, regulatory frameworks and policies have been issued in the last years (Sokołowski & Heffron, 2022). By providing smart policies and frameworks, governments can act as enablers, facilitators, and promoters by supplying clear information and establishing company goals and targets (OECD, 2022). Addressing the climate crisis requires cross-sector transformational actions that need government leadership and regulation (Atalla et al., 2022). Due to the complexity of this task, policies often fail in execution. According to Sokołowski & Heffron (2022), energy policy failures not only hinder the acceleration of the ET but can also have different negative effects on society, the economy, and international relations. For example, in the federal state of Bavaria, a law was passed requiring a minimum distance of ten times the height of a new wind turbine to the nearest settlement. This law has significantly slowed Germany's overall progress in the ET, through which no new applications for wind turbines were submitted in 2021 (Kyllmann, 2022a).

Also, carbon lock-in effects can postpone or hinder the roll-out of RE. For instance, Germany's plan to become independent of Russian gas is likely to result in a new dependency, creating a new carbon lock-in through a long-term energy partnership with Qatar (Brucker, 2022; Tagesschau, 2022b). Furthermore, on average, any financial resources invested today are locked until 2050, making wrong financial allocation a serious problem for the ET (Sato et al., 2021).

#### 2.1.3.6 Low Public Acceptance

The ET takes place at the local and decentralized level, reaching from solar panels on household-owned roofs to wind parks close to populated areas, and is closely linked to the population's everyday life (Energiesystemforschung, 2022). Social acceptance of REs builds the fundament for the success of projects related to the ET. However, the acceptance of wind energy can be low as it comes with externalities such as the impact on the landscape, noise, shadow flicker, and effects on the local ecosystem (Batel et al., 2013). There is also a reluctance on the part of society regarding battery storage, fearing explosion hazards and electro smog (Baur et al., 2022). The lobbyism organization “Vernunftkraft” joins active citizens by combining anti-wind energy initiatives represented by specialized lawyers (Clean Energy Wire, 2019).

## 2.2 The Circular Economy Framework

Most of our economic activity is based on a linear model following a ‘take-make-waste’ process. This means raw materials are disposed of as waste after extraction and subsequent transformation into goods and services (Dieguez, 2020; Rodríguez-Antón & Alonso-Almeida, 2020). Even planned obsolescence in design is expected to increase the production and consumption of even more products (The Economist, 2009). While the economy was able to rely on abundant supplies of readily available materials and energy during the industrial revolution, it has become more apparent that this linear model of economic growth is incompatible with the world’s finite resources, excessive waste production, and rising emissions, much less the sustainable future the world aspires to (Nguyen et al., 2014).

Humankind consumed raw materials consistently without considering the availability of reliable and sufficient supply in the future; more and more raw resources are being categorized as critical as their stock is declining rapidly (European Commission, 2011, 2020b). In addition to reducing supply, demand is anticipated to rise from a growing world population and an increase in wealth, especially in developing countries (United Nations Department of Economic and Social Affairs Population Division, 2022; Kharas, 2010). With more consumers, naturally, there will be a higher level of consumption.

To reach the EU’s ambitious goals of having humanity manage all-natural resources sustainably and produce zero waste by 2050, policymakers, scientists, and industry representatives are increasingly discussing shifting from a linear to a circular economy (CE) (European Parliament, 2019; Geisendorf & Pietrulla, 2018).

### 2.2.1 Definition of Circular Economy

The EU defines the concept of the CE in the EU Action Plan from 2015 as the following: A CE is an economy “where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste [is] minimised” (European Commission, 2015).

The use of these materials must be designed in a way that closes the loop. A CE approach considers all material and energy flows associated with a system or process and, thus, the entire supply chain of the energy source. This comes with a high degree of complexity, so CE strategies must be implemented at many different layers. Firstly, the CE model needs to be applied on three main levels – “the micro level (products, companies, consumers), meso level (industrial parks) and macro level (city, region, nation and beyond)” (Kirchherr et al., 2017, S. 224f). Additionally, CE strategies must be adapted in all life cycle stages – the design stage, the fabricant stage, the use stage, and finally, the stage in which the product reaches the end of its life (IEA, 2019). The roll-out of the transition to the CE model, replacing the ‘end-of-life’ concept, is rooted in three principles to achieve the implementation at each layer.

The first principle, “eliminate waste and pollution” is based on the circumstance that in a natural system, waste does not exist; the ‘waste’ of one species is the food of another. Humans have broken this cycle. They create a large amount of waste, the majority of which ends up in landfills or incinerators. A CE attempts to counter this by minimizing waste by treating it as a design flaw that can be fixed (Ellen MacArthur, 2022a). The second principle, “circulate products and materials” concerns the need to increase the life span of a product, either in its original form or that of the individual, disassembled components. The third and last principle “regenerate nature” is adapted from nature, showing that greater diversity leads to more resilience toward disruptions. (Ellen MacArthur, 2022a). Instead of focusing on extraction, the view should be shifted to regeneration. This principle is, therefore, not only about protecting the environment but also about actively improving it. Natural resources can be advanced and made more resilient by returning valuable nutrients to the ecosystem (e.g., the soil) (Ellen MacArthur, 2022a).

To put the three principles mentioned above into practice, the R-strategies were developed. The three original R's – 1. Reduce, 2. Reuse, 3. Recycle – were developed to create more circularity within the chain of production (Feng, 2004). This practical "how-to" approach of the R's is much more mature and granular today due to the advancement of research and practical adaptation. It is often associated with the ten R's (Recover, Recycle, Repurpose, Remanufacture, Refurbish, Repair, Reuse, Reduce, Rethink, Refuse) instead of three. All of them form the basis of a CE through their impact at the various stages of a product's life cycle (see Appendix D) (Potting et al., 2017).

### 2.2.2 Status Quo of Germany's Circular Economy

In Germany, there is no explicit institutional framework for CE to date, but various laws and guidelines are intended to guide its transformation. One important law is the "Kreislaufwirtschaftsgesetz" (KrWG 2021), which defines the waste hierarchy and targets 65% of all municipal waste to be recycled from 2020 (KrWG, 2021), which Germany overachieved by 67.4 % in 2021 (Weber & Stuchtey, 2019). Other important laws are the "VerpackG" for packaging waste, "AltfahrzeugV" for end-of-life vehicles, "BattV" for batteries, and "ElektroG" for electrical appliances. With a recycling rate of 64% of packaging waste, Germany is already notably more advanced than other EU member states. However, the country still has improvements to make in the areas of wood (Target 30%, status in DE: 23.6%), plastics (T: 55%, DE: 43.3%), and paper (T:85%, DE: 80.6%) to achieve the 2030 goals (UBA, 2022b).

Although Germany holds a pioneering role in collecting and recycling the waste in the EU, a closer analysis shows that it is still far from CE. A coherent package of measures on how Germany can become more recycling-proficient and active is still missing. Yet Germany holds several initiatives addressing only partial aspects of CE, a comprehensive “Circular Economy Initiative” was introduced in 2019. The initiative consists of the cooperation of three ministries, 24 businesses, and 22 research institutions to jointly develop a target picture for the CE in Germany and to identify concrete use cases and necessary framework conditions (Weber & Stuchtey, 2019). In 2021, the CE Roadmap for Germany was published with recommendations to guide decision-makers in politics, business, and science. Particularly the aspects of "circular business models", "packaging", and "traction batteries" are highlighted in the roadmap, and decisive recommendations are given regarding product, business model, socio-technical, and society. However, the central aspects of a systematic CE, such as the extension and targeted closing of product life cycles, have not yet been considered or only to an insufficient extent (Acatech et al., 2021).

Regarding the reuse of raw materials, Germany is far from a circular model, as more than 88% of the raw materials are built on new resources (Weber and Stuchtey 2019; Wilts, 2022). The circular material use rate shows how many material resources come from recycled waste. However, comparing circular material use rates, other EU countries such as the Netherlands (rate = 29), Belgium (21.8), and France (19.6) perform significantly better than Germany (12.9) (Eurostat, 2021). Germany's CE can therefore be more accurately described as "circular waste management” as products are not being sufficiently reused to prevent the volumes of waste we are currently observing from being prevented.

### 2.2.3 Benefits of Adopting a Circular Economy Framework

Currently, 45% of GHG emissions come from manufacturing everyday materials. A CE approach could reduce emissions, waste generation, and environmental pressure while increasing raw material supply security (European Parliament, 2015; Korhonen et al., 2018). From 2020 to 2030, the rate of substitution of various raw materials with recycled materials will increase. In the case of steel and aluminum, for example, which account for a significant proportion of raw material consumption in the German industry, the substitution rate is expected to increase from 44 to 58% and from 53 to 72%, respectively (Deloitte & BDI, 2021). Beyond its positive environmental impact, a CE is also beneficial for the economy. Through more efficient use of materials (e.g., waste prevention or eco-design), companies can save costs on materials and energy and be less reliant on resource dependencies, increasing their competitiveness. In addition, economic growth will be promoted with a boost in innovation (European Parliament, 2020). For the German gross value added, this would mean an increase of around twelve billion euros (Deloitte & BDI, 2021).

In addition, the general population as end-consumer will also be able to gain from this concept, not only through living on a healthier planet but also through the generation of new jobs (Korhonen et al., 2018). Projections estimate that alone in Germany, the advancement towards a CE will amount to around 180,000 additional jobs by 2030 (Deloitte & BDI, 2021). While jobs were initially predominantly related to design and engineering roles, the range is now increasing. A large proportion of the predicted jobs will focus on maintaining products and extending their useful life alongside those that involve AI or rethinking previous business models. Additionally, the CE creates jobs focusing on collaboration, right prioritization, and waste management(Wenzel, 2019). Besides this, consumers will receive more inventive and long-lasting items, improving their quality of life and long-term financial savings.

### 2.2.4 Challenges of Adopting a Circular Economy Framework

The transformation toward a CE also comes with various challenges, ranging from societal to technological ones. With more circularity, more complexity and interdependencies between stakeholders are created. A recurring issue within a circular system is that if one limitation is solved at one stage of the problem, a new restriction is often created at a different stage, only shifting problems to different parts of the cycle (Korhonen et al., 2018a). Such complexity and interdependencies do not only play a crucial role in technological terms, for example, in the supply chain but also in social ones. In today's global economic system, a high and increasing number of stakeholders is involved. These stakeholders are highly dependent on each other, creating a challenge as many companies and corporate environmental management efforts typically only focus on mitigating the environmental effects of a single, immediate activity (Robèrt et al., 2002). To manage inter-organizational cooperation to achieve sustainability studies, various questions need to be answered regarding responsibilities, budget, network organization, risks, and the distribution of possible benefits (see e.g., Seuring and Gold, 2013; Seuring, 2004; Korhonen et al., 2004).

Considering this complexity, interdependence is particularly relevant within or between different companies and at the country level. A wealthy country's attempt to become more sustainable by adopting legislation to protect the environment and its eco-efficiency could result in negative effects being transferred to a poorer country or might confuse the net impact of emission reductions through, for example, shifting waste to China (Korhonen et al., 2018). A switch to CE in Germany means that emissions within the country will increase by almost nine million tons due to recycling and reprocessing measures. In the overall balance, however, the emissions accounting decreases because no raw materials are mined abroad that must be imported to Germany. The net effect would correspond to a reduction of 5.5 million tons of emissions (Deloitte & BDI, 2021).

As downstream costs are not correctly priced, prices for virgin raw materials retrieved from the soil are usually cheaper than reused or recycled materials (second raw material). If the correct pricing was applied, companies would switch automatically (Witsch et al., 2022). German legislation is currently not focusing on adequate pricing as this is an international task, but it is trying to solve this issue by introducing laws that increase the use of secondary raw materials

(WEEE, 2012). However, due to a lack of concretization, authorities are limited in enforcing prohibitions which is the reason behind the semi-success of this path (Wilts, 2022).

Alongside these legislative or policy-related issues, recycled products face another obstacle. A technological cycle is very different from a natural cycle. Therefore, some argue that due to thermodynamic limits, a truly circular model cannot exist (Korhonen et al., 2018). A significant amount of energy is needed to search, collect, and recover materials – for which the infrastructure is also not in place yet. If humanity could fully tap the infinite energy source, the sun, and ensure the quality and pureness of the material in the recycling process, this limitation would be resolved. Currently, the efficiency, i.e., the conversion of incoming radiant energy into emitted energy of PV systems, only lies at 15 -20% (Kümpel, 2022). Since full recycling is not possible yet, a life-cycle assessment is performed to ensure that recycling efforts are worthwhile (Owen, 2004). To recycle products sufficiently, infrastructure needs to be provided. Material reflows are often not yet in place, as well as waste prevention initiatives (Deloitte & BDI, 2021). Actors in the latter field frequently lack the funding and personnel needed for projects to be successful (Wilts, 2022). But funding is not only a challenge for these stakeholders. Circular business models also tend to be more complex than linear ones. Additionally, to all these challenges, the issue of deeply engrained cultural and societal habits exists. Mindsets need to be shifted away from the convenience of consuming towards what happens after consumption, lowering the economic growth curve (Korhonen et al., 2018).

## 3 Methodology

The aim of this study is to determine how the circular economy (CE) framework could solve Germany's challenges in creating a sustainable energy system. Given the favorable positioning of the CE for integration in the energy transition (ET) in the background section, it was hypothesized that CE strategies could enable a sustainable ET. To broadly illuminate this subject matter from various angles, three sub-research questions (RQ) were formulated. They follow a funnel principle that incrementally increases the focus from a theoretical perspective to the practical integration of the CE in the ET.

**Sub-RQ 1** What is the relationship between CE and the ET as described in the existing literature?
**Sub-RQ 2** How could a CE be a solution for making the ET sustainable in the long-term?
**Sub-RQ 3** What does an alignment of CE and ET look like in practice and what potential limitations could occur?

The first question investigates the degree of academic linkage between the ET and CE to understand how much research on this approach exists. The second sub-RQ dives deeper into the issue by seeking the degree to which a CE can make the ET sustainable long term. The final sub-RQ completes the objective due to its practical orientation when analyzing the degree of alignment between CE and ET. Different methodological techniques were employed to address the three RQs.

To explore the first and second sub-RQs, a systematic literature review (SLR) was conducted. A SLR identifies, evaluates, and synthesizes results from current research evidence to provide more insights for evidence-based practice. This tool was suitable for gaining theoretical knowledge about the link between the two concepts as it was conducted to search for evidence that considers the CE and ET together in the existing literature (Boell & Cecez-Kecmanovic, 2015). The SLR protocol was initiated by retrieving data records from the Scopus database in October 2022 using specific keywords. In the first iteration, the terms *"Energy Transition" AND "Circular Economy"* returned 123 papers (see table 1). Next, they were scanned by title and abstract to determine their suitability for inclusion through the following pre-defined exclusion criteria:

- duplication of articles (1)
- no full access (9)

- inadequate scope or type of publication (17)
- country-specific context inhibiting general deductions (9)
- topic specificity without considering the ET‘s broader scope (13)
- language barrier (3)

After scanning the 123 papers for the exclusion criteria, 71 papers were left for review. Based on the findings in the first iteration, it was observed that the terms “Renewable Technology” and “Zero Waste” are frequently used as synonyms for “Energy Transition” and “Circular Economy”. To account for this observation, another search was conducted using the keywords *“Renewable Technology” AND “Circular Economy”, “Energy Transition” AND “Zero Waste”,* and *“Renewable Technology” AND “Zero Waste”.* This approach evidences a grounded theory approach as data collection was done iteratively and repetitively, later on, with various sources. The data output was expanded by 14 additional papers (see table 1) and screened under adherence to the same exclusion criteria leading to the dismissal of seven articles. In total, 78 publications were included, and 59 were excluded from the review (see Appendix E).

| **Search term** | **Numbers of publications (in English) found on Scopus** | **Publication period** |
|---|---|---|
| Circular Economy | 17,584 | 2004 – 2022 |
| Energy Transition | 11,415 | 1936 – 2022 |
| “Circular Economy” AND “Energy Transition” | 123 | 2015 – 2022 |
| “Renewable Technology” and “Circular Economy” | 9 | 2016 – 2022 |
| “Energy Transition” AND “Zero Waste” | 3 | 2021 – 2022 |
| “Renewable Technology” AND “Zero Waste” | 2 | 2009 – 2016 |

*Table 1: Overview of the numbers of articles returned per search with different keywords and publication periods*

To answer sub-RQ 1 and determine the relationship between the two concepts, quantitative and qualitative analyses based on the SLR were conducted by considering article quantities, publication dates, and key messages, further described in the succeeding sections. The second sub-RQ was addressed by clustering the topics of the included publications into overarching themes and analyzing their findings regarding CE and the ET. Finally, sub-RQ 3 was approached from five different perspectives, which were deducted from the results of the SLR. Each entails an individual investigation whose results contribute to the broader objective of answering sub-RQ 3.

The first topic concerns CE in the wind energy sector in Germany and was treated through a mixed methods approach comprising an in-depth literature review and two case studies based on qualitative interviews and available secondary sources. The approaches of Siemens Gamesa Renewable Energy and Neowa were analyzed in detail as solutions for blade recycling. The second investigation follows the same approach as the previous one to explore how a CE can be implemented along the lifecycle stages of photovoltaic (PV) solar energy technology in Germany. Here, the cases of Solarwatt, Enpal, and Solarmaterials were analyzed. Thirdly, the German battery recycling industry was thematized through a structured literature review and a case study with unstructured interviews regarding the business case of Circu Li-ion. The fourth topic, CE through energy efficiency (EE), was researched through a structured literature review and a case study in the building sector of German energy services company Wegatech based on secondary sources. A final investigation concerned the transnational sourcing of emission-free energy carriers from MENA, exemplified by the Desertec Desert Energy mission. For this purpose, an analysis based on a structured literature review was conducted which was complemented with twelve semi-structured qualitative interviews.

These practical cases were selected to assess the adoption of a CE approach in the German energy market and the realistic degree of compatibility for the integration of CE in the ET. This insight into current market solutions expands the academic findings of the SLR and yields a more comprehensive approach to data collection as it extends beyond academic research to market developments.

It should be noted that the collective approach taken to investigate the objective of this study is based on grounded theory. The SLR enables an inductive discovery of new theories based on collecting and analyzing qualitative data in an iterative process (Corbin & Strauss, 1990). Furthermore, real-world data from interviews and market case studies were used to answer the sub-RQ 3. Hence, the data collection occurred cyclically since the academic papers in the SLR were screened in a two-stage process, and current market evolutions were continuously analyzed in case studies and theoretical samplings.

# 4 Data Analysis of the Systematic Literature Review

In the following section the data from the SLR is analysed quantitatively and qualitatively with respect to sub-RQ's 1 and 2.

## 4.1 Alignment of the Energy Transition and Circular Economy in the Literature

To answer the first sub-research question (RQ) "What is the current relationship between CE and ET as described in the existing literature?", the number of papers per search and the view on combining CE and ET, and the key message of each publication, were analyzed. Appendix F shows a summary of the perspectives on the relationship between CE and ET of all articles and an indication of how their combination is viewed in the literature, including quotes and information that justifies the authors' classifications.

### 4.1.1 Quantitative Insights

The number of publications obtained from the SLR per search provides some insights into the extent of integration of the concepts of CE and ET. This shows whether their combination is already a common occurrence in the literature and how much research into the area exists.

Searching Scopus with the keywords „Energy Transition" and "Circular Economy"' separately yielded 11,415 and 17,584 articles, respectively (see table 1). The more significant number of publications for CE could be attributed to the fact that it is a very fixed concept with clear principles, while ET is a more complex process under whose umbrella many sub-areas fall. This may invite the scientific community for more direct research into topics directly related to CE, while the areas associated with ET investigations can be more far-reaching and tagged with different keywords, for example, „Energy Efficiency" or „Transport Electrification". However, this and similar lines of reasoning in the following section are based on the somewhat subjective estimations of the authors and must be considered carefully.

Their respective publication dates further suggest that both topics have been discussed separately in different periods; the first article related to the ET is from 1936, and the first on renewable technologies in 1999, while the first on CE was only published in 2004. By contrast, the articles that address both concepts were first introduced in 2015, indicating that merging the two subjects is a novel trend that has increasingly gained traction in recent years (see Appendix E). The popularity of research into both topics in combination has increased over the years, reaching its momentum in 2015 – 2016, coinciding with the Paris Agreement's launch year. It is likely that the urgency for both movements conveyed by the scientific community in recent years and policy developments such as the Paris Agreement had a significant impact on the amount of research invested into these areas at the time.

Since the present paper aims to investigate the coupling of the ET and CE in Germany, the locations of existing publications were of interest to the authors. Analyzing the most common publishing locations of the articles, notably, three out of the top five countries are in Europe (see Appendix E). This suggests that linking the two concepts has gained interest in the EU as scientists address the topic. Considering that it is more effective for countries to act together in Europe rather than on their own, this is of utter importance (BMWK, n.d.). Furthermore, the fact that China is in the top five at number four was expected as China is considered a global pioneer in terms of the ET and CE. Germany, in 5th place with eight publications, falls clearly behind its' European neighbors, such as the Netherlands (18) and Italy (19), despite being one of the strongest economies.

When the database was searched with the two keywords in combination using „AND", the output was narrowed down to 123 publications. The combination of the two terms thus accounts only for a small share of the total body of research on both topics. This indicates that while CE and ET have been considered extensively in the literature, the concepts are integrated with each other and researched in combination to a much lesser extent. Furthermore, even when extending the search with keywords often used interchangeably for CE and ET, the output was expanded by 14 articles.

The novelty of the topic and the evident literature gap provide a sound justification for the exploration of aligning ET and CE in the present paper. When analyzing the publications that combine the two terms, it becomes clear that while the area is large and promising, there is room for more research directions to be explored.

### 4.1.2 Qualitative Analysis

In addition to how much CE and the ET are combined in the literature, the nature of their relationship is also relevant for an in-depth understanding of their academic alignment. While reviewing the remaining articles after the exclusion, a noticeable difference in how the relationship between the two concepts is viewed in different papers became evident. Four perspectives were identified:

- A CE must be implemented in the ET for the transformation of the energy system to be successful and sustainable (43).
- The ET is needed to achieve a true CE (10).
- CE and ET should be integrated to advance each other (18).
- The two concepts are viewed separately and decoupled from each other (7).

The most frequent form of association is the idea that the CE framework is necessary to achieve a successful ET in the long term that is entirely green (43). This promising finding reinforces the aim of the present study and, due to its' relatively low representation in the literature, encourages further research into the area.

A contrary perspective in the literature views the matter from the opposite point of view in which the ET is necessary to achieve a truly circular system (10). In this context, it is often mentioned that the CE faces natural limits and large subsectors are energy intensive. Therefore, without the transformation to REs, circular efforts are only possible or sustainable to a limited extent since, for example, current energy sources deplete critical raw materials and produce large amounts of carbonaceous waste that must be reduced or recycled.

There is some evidence in the literature (18) of the consensus that CE and ET must be considered in alliance to achieve progress in both transitions. These articles agree that one change cannot happen fully without the other. Most commonly, these articles reference their synergistic effects in reducing energy demand and GHG emissions and their contribution to ecosystem regeneration to justify this viewpoint. As they are both system-based approaches, their holistic impacts, such as links to improved social welfare and justice, are referred to when explaining the need for a circular green economy.

Only some papers (7) from the search consider the two concepts decoupled. These articles reference either one of the two concepts or separately without evidently linking them when discussing overarching topics. They include waste, global supply chains, smart cities, technology, business model innovation, AI, and under-researched areas in health. All these articles were excluded from further analysis hereon since their key messages were irrelevant to answering RQ 1 further.

#### 4.1.3 Academic Positioning on the Integration

This section intends to show how favorable existing research findings from the remaining articles (71) are for combining the ET and CE. After establishing the extent of the linkage between CE and ET in the literature and the perspective from which current research investigates the topic, the key message of each article was extracted (see Appendix F). This serves the purpose of making initial inferences about the general tone of the literature toward the potential for aligning the two concepts. Finally, three stances on combining the ET with a CE were identified:

- It has a strong potential for beneficial outcomes with minor limitations (49).
- It has potential beneficial outcomes but faces serious challenges (7).
- It has been shown to work in practice and is desirable and feasible (15).

Most publications (49) frame the implementation of CE in ET, that of ET in CE, or the use of both concepts to achieve each other positively and make promising conclusions. The topic areas of these papers include but are not limited to, critical rare materials like copper and cobalt, EV batteries, and supply chains. Some of the most discussed levers for potential include an improvement in energy and resource efficiency, a transition to renewables, and circular business models. While these papers recognize the potential for integration and view it as favorable, some reference minor limits to implementation. A more in-depth analysis of these and the topic areas are presented in the succeeding section.

Some papers that see potential conveyed that integrating the concepts in any form, although desired, faces more serious challenges that could significantly impact the implementation (7). These challenges include the limits of CE in resource extraction, where responsible sourcing is the better solution, and too much waste is generated, reducing a CE system's cost competitiveness. Low profitability is also a factor in the discussion around biogas topics and battery recycling, which faces challenges due to its process complexity. There is also a limited effect of coupled energy and CE transitions on material flows in today’s fast-consuming society.

Finally, several papers (15) conclude that coupling the two concepts has already been shown to work in practice and hence is desired and feasible. Some areas evidenced by this include transport electrification, CE villages, waste-to-energy conversion, grid integration, and renewable implementation.

To conclude, the most commonly represented perspective in the literature about the integration of CE and the ET is that it is desirable and feasible. Yet only 15 articles provide evidence that their combination has successfully taken place in practice in various areas. Furthermore, a range of challenges on this journey is being discussed. This further justifies the research objective of the present study, exploring ways to implement the CE framework in the ET and the practical approach taken in the later sections.

## 4.2 Analysis of the Solution-Orientation of the Literature per Sub-Topic on Integrating a Circular Economy in the Energy Transition

The objective of the following section is to deduct the degree of reference of circular economy (CE) and the energy transition (ET) among their most frequently discussed key topics to determine their integration in practice. The records in the systematic literature review (SLR) are clustered into five overarching topics: critical finite resources, clean energy technologies, battery and mobility, data and AI, and policy (see Appendix H).

### 4.2.1 Critical Finite Resources

Within the scope of the SLR, the discussion about the intersection of critical rare-earth resources and the ET takes priority. 18 papers dedicate their scope to this. The overarching problem is that the construction of renewable energy (RE) technologies depends on the supply of finite resources like cobalt and other raw materials (Rahimpour Golroudbary et al., 2022). It is uncontroversial agreed that the increased intensity of REs is not aligned with the material constraints needed for production. Different approaches to mitigate this challenge are taken.

Various authors agree that technological improvements are required to expand product lifecycles and thereby achieve reductions in material demand (Koese et al., 2022). It is also argued that innovative technologies for lower raw-material input intensity should be driven (van Oorschot et al., 2022). This idea of applying the "R" principle re-think is further mirrored in the context of prosumers, people who consume and produce energy, which have a growing prevalence. It not only fosters a culture of clean energy sharing and resource utility maximization but also contributes to the stability of the energy system (Gimeno et al., 2020). It complements the view that the problem of reaching limitations to the finite input resources for REs is a shared responsibility across the globe (Haas et al., 2015; Wei et al., 2022). The novel, increasing demand for investigations into the dependence of the ET on critical resources is highlighted (Srivastava & Kumar, 2022). Finite raw materials can be considered part of the macroeconomic perspective due to the dependency on international exports and imports.

The innovation focus is complemented by the need to recycle outdated technologies of the utilized finite resources like cobalt and lithium. In this regard, China is referred to as having a leading role in implementing a CE. The country has introduced measures to accelerate steel and copper recycling which will likely entail positive consequences for the country's competitiveness given the current material scarcity (Dong, D. et al., 2022; Nechifor et al., 2020). The potential for savings in energy use and a decline in $CO_2$ and fine particles emissions is further demonstrated by a net saving calculation for a CE scenario in China (Su & Urban, 2021). Beyond Chinese activity, the whole recycling industry for EV batteries use is growing (Samoylov, 2019). Yet, it is controversial to what degree recycling raw materials would narrow the supply of primary demand, which demands further investigation (Dong, D. et al., 2022). But it is agreed that governmental regulations, an increase in recycling rates, and a mindset shift toward secondary production will have an impact (Abdelshafy & Walther, 2022; van der Voet et al., 2019).

In addition to the need for innovation and recycling, the organization of global supply chains for importing and exporting the required resources is discussed. The transnational sourcing of and dependence on materials, coupled with the instability of global supply chains, entails geopolitical risks (Sun, 2022). Furthermore, global supply dependencies are prone to fluctuations and price instabilities (Earl et al., 2022). These geopolitical risks should consider the CE principles so that new strategies must be developed to meet the supply-demand challenges (Guglietta et al., 2022). To encounter the challenge of balancing demand and supply and to improve supply chains, an accurate, cumulative prediction of required metals for the ET must be focused on (Rachidi et al., 2021). A final paper also emphasizes the impossibility of a truly CE (Valero & Valero, 2020).

The authors deduct that the importance of the critical metals for ET is undisputed. However, there is yet no clear roadmap that serves as guidance to mitigate the challenge of meeting the demand for critical metals. Several attempts have been made through increased recycling, technological innovations, and governmental enforcement. Nevertheless, it can be concluded that the dependence on finite resources is a major point for discussion that requires more attention in the literature based on research and development.

### 4.2.2 Renewable Technologies

The RE sources wind, solar, and biogas and their respective technological hardware were referenced in various publications in the SLR. The following section analyzes their challenges, limitations, and opportunities concerning CE implementation in the ET.

#### 4.2.2.1 Wind Energy

The CE is discussed in the context of wind energy in four papers. The main issue lies in the recycling of materials after decommissioning the wind turbines. Both the resulting waste and the loss of necessary critical materials were highlighted (Mulvaney et al., 2021, Velenturf et al., 2021, Bleicher & Pehlken, 2020). In addition, it is highlighted that there is a supply risk of critical minerals as wind technologies are expanding, and CE could pose a solution for this (Bleicher & Pehlken, 2020). While some research is focused on the challenge of recycling the wind blades in particular (Mulvaney et al., 2021), others address the recycling of offshore wind farms (Velenturf et al., 2021).

Given that the prevalence of offshore wind farms will grow rapidly in the coming years over onshore farms, Velenturf et al. (2021) emphasize the lack of a common recycling approach to this technology and, again, point to a CE as a solution. This prediction stresses that integrating a circular economy into the design, development, operation, and End-of-Life (EoL) stage of offshore wind energy can employ high-quality end products, saving resources and including competitive advantages. A CE will also enhance opportunities to create or grow local supply chains and new market opportunities (Bleicher & Pehlken, 2020). The publications also identified challenges for introducing a CE concept in wind energy. There is often a lack of political regulations to provide more incentives for developing the required recycling infrastructure (Mulvaney et al., 2021).

Without a multi-sector perspective and approach, the conception of CE will face serious hurdles (Velenturf et al., 2021).

#### 4.2.2.2 Solar Energy

Seven papers specifically address CE in solar energy (see Appendix G). The literature positions photovoltaic (PV) panels as one of the most significant contributors to electro waste in the future (Mulvaney et al., 2021) and emphasizes the urgency to integrate a CE in the production and decommissioning of the PVs (Kim & Park, 2018, Mirletz et al., 2022, Duran et al., 2021, Velenturf et al., 2021).

CE is seen to recover the valuable materials used in the production of PV, in particular glass cullet, silicone, and silver (Mirletz et al., 2022a; Mulvaney et al., 2021). Using recycled materials can save up to 50% of the energy used in production, and especially the recycling of glass back to flat-glazed could avoid many emissions associated with decomposition (Mulvaney et al., 2021). Mirletz et al. (2022) analyzed two circular approaches: Life extension and closed-loop recycling, whereas both approaches hold the ability to mitigate primary material residues and lifecycle waste. In addition, a CE enables the expansion of local supply chains and the opening of new markets and business opportunities (Razzaghi Asl, 2022; Velenturf et al., 2021).

However, implementing a CE in solar energy is not seen as convenient and faces multiple limitations. For instance, a major problem is the lack of waste management infrastructure to develop a secondary market (Mulvaney et al., 2021). In addition, both the collection process and storage opportunities are missing (Kim & Park, 2018). The main reason for this is that, to date, PV waste volumes have been manageable, and there have been no incentives from the government or the market to build the necessary infrastructure (Kim & Park, 2018; Mirletz et al., 2022). Furthermore, PV waste technologies have so far been highly cost-intensive, and the best available technology is not yet commercially viable. To change this, more incentives for investments in R&D

projects related to PV waste, such as PV recycling, design, and monitoring, are needed in the future through policy regulations (Kim & Park, 2018). Finally, many PV systems are orphaned as their original manufacturers no longer exist to take responsibility. In this matter, it becomes necessary to clarify who is responsible for this waste and the recycling cost (Duran et al., 2021).

#### 4.2.2.3 Biogas

In total, eight papers discuss biogas production with regard to CE. Its' procedure uses biomass and is based on the CE model, as organic waste is used to generate energy. This reuse of waste materials instead of' end-of-life disposal reflects a more conscious use of resources (Salladini et al., 2019). For this reason, biogas does not address the CE approach to reduce resulting waste streams from the energy source itself, but instead, it provides the basis for the procedure and the successful implementation of bioenergy projects. Some papers linking biogas and CE focus on the necessary steps to successfully implement more bio-energy projects and highlight the existing limitations (3).

While biomass has often been underestimated as an energy source, it is now receiving a revival through the debate on CE (Lyytimäki, 2018). Yet, in most Asia-Pacific countries, waste-to-energy does not play a significant role even though it benefits efficiency in natural resource use and reduction of emissions. For example, in the case of Sri Lanka, introducing a waste-to-energy approach positively impacts overall grid emission accounting and results in savings of almost 180,000 tons of GHG emissions annually (Samarasinghe & Wijayatunga, 2022). One other paper highlights the importance of the role of bioenergy for carbon capture and utilization in reducing industrial emissions and producing low carbon gases by monitoring and reporting the fossil and biogenic emissions (Koytsoumpa et al., 2021). However, with biogas, too, several limitations prevent rollout. A significant problem is the organization and coordination of the stakeholders and their interests (Niang et al., 2022).

Furthermore, establishing a procedure for the waste's delivery, storage, and processing is often non-existent and complicated to plan (Fytili & Zabaniotou, 2022). Additionally, insufficient government incentivization is available here (Niang et al., 2022). Furthermore, many projects are not yet profitable and encounter resistance from the local populations. Education and funding would solve these problems and provide opportunities for new business models (Lyytimäki, 2018).

Despite these findings regarding efforts to implement various RE sources more sustainably, research that would complete the picture of the emissions generated by REs after the complete phaseout of fossil fuels is lacking. There is little evidence on how the switch to REs will close the gap to the 1.5-degree climate target (Schwartzman & Schwartzman, n.d.). Furthermore, the shift to REs needs to be considered from a multilateral perspective, including competition for capital, changes in electricity prices, the net loss of employment in conventional energy sources, and other dimensions. One paper suggests that a critical consideration demands a meta-evaluation and regression (Stavropoulos & Burger, 2020).

### 4.2.3 Batteries, Energy Storage and Mobility

Another cluster recognized through the SLR involves energy storage and related electrification matters, specifically in transport, mainly discussed in cases around electric vehicles (EV) and energy storage systems.

Seven papers address batteries and mobility and are often connected to topics in recycling. Evidence shows that battery reuse and recycling are essential for energy supply (Srivastava & Kumar, 2022). A key finding is that current recycling practices are inefficient in enabling a true CE. One reason for this is impure waste which raises the necessity for waste segregation and collection. Pretreatment through dismantling is time-consuming but highly beneficial for further processing (Mulvaney et al., 2021; Tabelin et al., 2021). E-waste collection and recycling percentages have the potential to increase through the improved engagement of individual household waste segregation (Tabelin et al., 2021). There is a consensus that waste is a valuable resource for a CE approach on an industrial scale as it forms the base for feedstocks in industrial metabolism. So far, there is a lack of consistent and strong business cases, which hampers the deployment of recycling in more complex commodity systems. Integrating waste in clean technologies across industries is fundamental for decarbonizing electricity and mobility (Mulvaney et al., 2021).

Some papers address the financial attractiveness of recycling models (3). For example, although the price for lithium-ion batteries from EVs is decreasing annually due to more demand and competition in this sector, there is a need for stronger price drops to make more recycling business cases feasible (Samoylov, 2019). One way this could become a reality is by increasing the supply of lithium-ion batteries from EVs ready for disposal (Lima et al., 2022; Mulvaney et al., 2021).

Four papers also point out that securing the supply of raw materials required for EV batteries is critical due to their relative scarcity. There is an agreement that sourcing components like lithium, cobalt, and rare earths face environmental issues, ethical concerns, uneven distribution of reserves, and risk of supply (Samoylov, 2019). Often single components such as rare earth magnets are, although so essential, understudied regarding their environmental impact (Bonfante et al., 2021). Therefore, the full extent of this activity remains uncertain. Moreover, and as previously acknowledged, the uneven distribution of critical raw materials can foster risks in the supply chain, holds the tendency of governments to assert control over territorial resources (resource nationalism), and can lead to geopolitical risks. These risks endanger raw material security, whereas the preservation in the usage cycle must be maximally exploited. As a result, CE principles are essential for acquiring most of the resources and ensuring a just ET (Srivastava & Kumar, 2022). In addition, low-carbon infrastructure can create opportunities for component reuse and reduce reliance on critical resources (Busch et al., 2017).

Mulvaney et al. (2021) sum up this consensus by inferring that the implementation of CE is still in the early stage since the current focus is more on recycling than the reuse principle. This prioritization can be seen in the significant progress in waste management and recycling rates in several countries. Nevertheless, the consciousness should not only be acknowledged in the recycling state, but greater adoption of circular and clean production, an increased producers and consumer responsibility, and the adoption of policies fostering CE must be in place. The transition to a truly CE must involve different stakeholders of the society and their capacity to collaborate (Mulvaney et al., 2021). This shows the necessity for economically and socially feasible recycling business cases of, for example, lithium-ion batteries coming from EVs or other sources. To keep up with the high growth of electrification, the lifetime of raw materials needs to be utilized in the best way possible.

### 4.2.4 Artificial Intelligence and Data Management

Nine papers focus on data-driven approaches to the CE in the ET. Artificial intelligence, blockchain, and other advanced data management solutions to integrate CE principles are covered in this context and connected to smart cities and energy efficiency (EE) improvement.

The application of artificial intelligence in the field of CE is wide-ranged. Related technological innovations and REs have a mutual positive impact (Khan et al., 2022), but intelligent solutions are specifically applied to disassembly and recycling (Meng et al., 2022). In EVs, intelligent battery disassembly positively impacts performance sustainability (Meng et al., 2022). Data tools in the form of computational algorithms can help increase transparency on platforms, thus fostering investment decisions into green technologies, such as carbon capture and storage (Abdul Manaf et al., 2021). Data management in the form of blockchain technologies is also beneficial when sharing and validating information between several parties. Smart tools containing and communicating data like supply, demand, or quality between waste segregation, recyclers, and manufacturers can minimize the amount of waste being incinerated and thrown away by forecasting demand and determining production needs (Sankaran, 2019).

This is also applicable for use in smart cities (Montakhabi et al., 2021), which are connected to artificial intelligence and data in multiple ways (8) (see Appendix H). In this context, roadshows combine competencies and efforts of different stakeholders to build capacities and spread initiatives for a sustainable ET in Europe (Pulselli et al., 2021). Another approach to smart cities is initially developing an implementation process at a smaller scale, like a CE village, which is already feasible in practice due to smart data management (Liaros, 2022). In this context, microgrids, small-scale self-sufficient energy systems, are referenced as they could irrigate local food systems in future cities. Furthermore, regenerative villages need to be developed that build upon a distributed network, are virtually connected, and integrate sharing principles such as electric vehicles. (Liaros, 2022). This scenario considers energy self-sufficiency as a way of achieving sustainable development which relates to the integration of society for the ET (Barragán-Escandón et al., 2017). Inclusion and empowerment of the population are not only essential for building a smart city but also result in innovation potential and form a niche for opportunity at the European level (Arias et al., 2022).

All papers conclude that there is a positive potential for combining data-driven solutions with the concept of CE within energy topics, specifically for recycling techniques, smart cities, and using available energy most efficiently. However, literature combining data, smart city, and CE is limited by only emphasizing the feasibility of micro- and not larger cities. Finally, economic feasibility and real-life practicability must be assessed, as most papers have a theoretical basis.

### 4.2.5 Regulatory Environment

Finally, the SLR clustering resulted in 12 articles covering CE and ET enforcement policies. The need for required regulations comes along with the challenges resulting from ET interventions that are highly mineral intensive and rely on CRM. Therefore, Bleicher & Pehlken (2020) agree that policies, in this context, should relate to the material basis of ETs, such as the CRM. For example, policies could address the estimation of the need for CRM or certification schemes. However, most literature focuses on policies covering economics and geopolitics, but little research is conducted on policies related justice of CRM (Srivastava & Kumar, 2022).

Nevertheless, it is agreed that effective policy action is critical for developing CE and ET (Okafor et al., 2021). Another position is that community energy initiatives are represented as one solution to enforce CE principles. Therefore, policies must not only relate to governmental enforcement but community energy initiatives that consider CE principles also hold great potential on a small scale that can be replicated (Mishra et al., 2022).

In the case of port cities, it was established that they do not yet count as one comprehensive entity as discrepancies between port and city values and objectives are held (de Martino, 2022). Therefore, one can infer that policies cannot be applied universally (de Martino, 2022). In this scenario, the importance of the triangle cooperation, including business, government and society plays a critical role. It is further shown that the pathway to a low-carbon future driven by CE principles must be enforced on a multilevel approach aiming toward one goal (Kalchenko et al., 2019). This article also assesses the potential of foreign best-practices to adopt nationally, specifically in the case of Russia. The author could deduct that the introduction of a CE in the ET also demands educational work through a global and macroeconomic perspective. However, policies must be replicated on a large scale and for RE self-consumption and microgeneration. Accordingly, financial resources and frameworks must be ensured (Scarpellini et al., 2021).

Chapters *2.1* and *2.2* showed that policies related to CE and ET hold a broad scope. Superficially, the introduction of policies, institutional instruments, and innovations related to lifetime extension and recycling rates are needed to the reliance on CRMs (Ishaq et al., 2022; Watari et al., 2021). Again, it is widely researched that critical materials to manage the ET lack viability and end-of-life disposal strategies, which yield critical consideration from a legislative perspective (Mulvaney et al., 2021). Further, it is suggested to include policies on introducing smart cities to achieve decarbonization to fight climate change  (Arias et al., 2022). However, the ET faces new technical and socio-economic challenges that demand legislation. For example, the clean energy method of power-to-gas faces limits in investment and the choice of territory for the facilities entails social and economic barriers. Therefore, effective policy making adopted to the given barriers is needed (Llera-Sastres et al., 2020).

To conclude, incorporating a CE in the ET is evident in multiple publications and is increasing in the current academic literature. However, considering the relevance of a full lifecycle embodiment of CE in ET, the current quantity of publications is rather underwhelming. The discussion regarding the identified clusters revealed that the literature already discusses well-grounded approaches, but the alignment of a CE in the ET still faces limitations and unclarities. In particular, the consideration of wind, and solar energy, as the driving clean energy sources in the context of ET still feature a low penetration in publications, contradicting the significant requirement. Therefore, today, it cannot be stated that a CE is fully embodied as a complementary concept as part of ET. To validate this outcome, the following individual parts will further add to the market and practical consideration of the integration of CE in the ET.

# 5 Practical Cases on the Integration of the Circular Economy in the Energy Transition

Wind and solar energy appear as the two key renewable energy (RE) sources of the future as their theoretical potential for energy production exceed the demand (EREC, 2010). However, the sustainability of both energy sources is threatened by vast waste generation and dependence on critical resources. In addition, the grid's supply security cannot be guaranteed due to its volatility, so power storage systems are required. Batteries and power storage systems face similar issues as solar and wind on their path to becoming fully sustainable. Simultaneously, all resources, ranging from CRM to the energy produced, must be used in the most efficient way possible to protect the system from resource constraints. Complementing the perspective of efficient resource utilization, importing emission-free energies from countries with higher solar or wind occurrences to Germany must be considered. To obtain a full perspective, global energy trade implying opportunities and challenges and leverage on the acceleration of ET must be discussed. This discussion is placed under the umbrella topic of the incorporation of CE in ET, whereas Germany must not only benefit from the imported energy carriers but must contribute as a role model in CE practices.

All these aspects play a critical role in the transition towards a clean energy future. Therefore, their respective considerations of CE framework and degree of impact for the ET will be analyzed and critically discussed. Hence, the following sections exemplify five practical cases for CE application: wind energy, solar energy, battery storage, EE, and emission-free energy trading in the MENA region for the German ET.

## 5.4. Circularity in the German Battery Industry – A Case Study of Circu Li-ion

### I. Introduction

The energy transition in Germany is heavily exposed to the electrification of its economy. This advancing electrification, especially in the mobility sector, is powered by lithium-ion batteries (LIB). Electric vehicles (EVs) are increasing sharply in numbers as unit market sales are expected to reach 1.629.400 vehicles in 2027, coming from 391.000 in 2020 (Statista, 2022a). Furthermore, Germany has, with 150.000, the highest number of electric scooters in Europe (Baxter, 2022). That development results in lithium overdemand as it is estimated that 700% more lithium is needed by 2030 globally compared to 2021, which can be replicated to Germany based on the mentioned developments (Azevedo et al., 2022).

Following this development, Germany's dependence on countries exploiting the highly scarce and cost-volatile lithium increases. More than 60.000 tonnes of batteries are placed on the German market every year (Federal Ministry for the Environment, 2022). Depending on the application, LIB reach their EoL after a maximum of four years for micro-mobility and after 15 to 20 years for EVs, respectively (Hello Mobility, 2021; Turcheniuk et al., 2018). Therefore, Germany will have to deal with increasing amounts of battery waste on a yearly basis. To mitigate dependencies and waste issues, the life of the valuable resource lithium must be prolonged.

Therefore, raw material use must be optimized from an environmental but also a business perspective. To do so, the integration of CE principles is the best way to maximize the life of raw materials (Bell, 2020). Currently, recycling builds the predominant technology for treating EoL LIB (Hagelüken & Goldmann, 2022). Against the public perception though, traditional battery recycling methods are far from providing sustainable circularity as they are resource-intensive and inefficient (Hirschlag, 2022). Thus, there is a clear need for innovative and green solutions to increase recycling rates. This is why this section of the study aims to analyze current LIB recycling processes. Furthermore, it will present a solution to its issues by conducting a case study about a startup tackling this industry failure. Finally, on the basis of this case study, core findings and recommendations for a more sustainable battery ecosystem in Germany are deduced.

## I. Background – Inefficiencies of Traditional Recycling

To understand the potential and pitfalls of traditional recycling, the following section provides an overview and analyze current recycling methods of LIB. As LIB are the most popular storage controlling over 90% of the global grid market, the following study focuses on these kind of batteries (Campbell, 2022). Their popularity is connected to their efficient energy-to-weight ratio, high open circuit voltage, low self-discharge rate, no memory effect as well as a slow loss of charge when not in use (Qiao & Wei, 2012).

As the structure of LIB is highly complex, they must be preprocessed before being reused or recycled (Baum et al., 2022). That is mainly connected with the risks of explosion or combustion if batteries are not preprocessed accordingly. To minimize this risk from the beginning, LIB are discharged and dismantled before the actual recycling process starts. Afterwards, either hydrometallurgical, pyrometallurgical or direct recycling follows (Bae & Kim, 2021; Zhou et al., 2020).However, direct recycling will be neglected in the following as it is still in research and development phase and not adopted on mass production scale (Kohll, 2022).

When discharged and dismantled battery cells enter the pyrometallurgical process, they are firstly preheated with below 300°C to remove organic material with evaporating electrolytes (Bae & Kim, 2021). Afterward, they are crushed before the actual pyrolysis follows, with temperatures of over 700°C, to remove the remaining plastic, followed by a smelting reduction. This burning leaves a black mass (Zhou et al., 2020). Here, valuable resources such as lithium are either destroyed or left in the slag without the opportunity of being recovered (Kohll, 2022). Simplified, the pyrometallurgical process is characterized by continuous shredding and burning at different temperatures, leaving a slag without the opportunity to recover lithium, but only other metals such as nickel or manganese (Kohll, 2022).

When discharged and dismantled battery cells enter the hydrometallurgical recycling, they first undergo another pretreatment procedure to keep the cathode active materials and remove the rest. Afterwards, several steps of active and reductive leaching with mineral and organic acids follow. Following, the metal is separated using solvent extraction, ion exchange, and precipitation after metal processing (Petranikova, 2020). The resulting metal ion solution is the basis for new products as it includes several valuable raw materials such as lithium (Zhou et al., 2020).

Comparing both processes, it can be stated that on a global scale the pyrometallurgical process is more adopted than the hydrometallurgical process. One of the reasons is that the current recycling ecosystem is focuses on the recovery of nickel and manganese as those are the major raw materials with a value chain infrastructure in place (Kohll, 2022). However, pyrometallurgy recycling is way less efficient and can save close to no lithium (Kohll, 2022). Furthermore, hydrometallurgical recycling is more sustainable as pyrometallurgy is known to generate high amounts of emissions such as GHG (Yu et al., 2022). Hydrometallurgical recycling needs less energy inputs such as diesel or electricity and overall recycling costs are lower, but it requires more than double the material input (for example, sulfuric acid or hydrogen peroxide). However, as fluorine compounds and low-molecular-weight organic compounds could be mixed into the solution, wastewater treatment for hydrometallurgy is extremely pricy and complex (Qi, 2018). For both processes, it can be stated that manual preprocessing, such as dismantling is expensive and takes long when done manually as well as unprecise and wasteful when done with currently used automation (Willuhn, 2020) (appendix K.II).

Concluding, even though hydrometallurgy is more efficient and sustainable than pyrometallurgy recycling, it is less commonly adopted and still leaves major room for improvement. However, Recycling companies like Umicore have been using the mentioned processes for years (Umicore, 2022).

As the electrification of the economy booms, demand for LIB increases. Globally, lithium demand is projected to be 166.000 tonnes higher than supply as early as 2023 (Paul & Aich, 2021). Also, with increasing new LIB on the market, more and more reach their EoL. A study by the Frauenhofer ISI institute shows that the volume of LIB that need to be recycled could be about 230 kilotons per year in Europe by 2030 and might grow to about 1.500 kilotons per year in 2040 (Neef et al., 2021). With increasing volume, the pressure to regulate LIB disposal and focus on recycling technologies has increased. Therefore, there has been increasing interest in LIB recycling, but current market participants will not be able to meet the flood of discarded LIB as it would require annual growth rates of more than 30% until 2030, which is not feasible with current planning (Neef et al., 2021). With current projections of EoL LIB ready for recycling, there is still no clarity which process will dominate the recycling industry as current recycling face issues around commercialization and environmental concerns (Bae & Kim, 2021; Neef et al., 2021). Moreover, there are concerns about efficiency as current recycling methods have been focusing on more valuable metal recovery, which results in a lithium recovery rate of only <1% globally (Swain, 2017). Thus, there is a clear need for a sustainable solution to increase recycling efficiencies and prolonging battery cell life.

## II. Methodology

To fully grasp the topic of LIB recycling and find solutions for its inefficiencies, a mixed- methods approach was used. To better understand the technological status quo and current business models of LIB recycling, a structured literature review was conducted in the form of secondary research. Here, the Scopus database was searched using the combination “lithium AND battery AND recycling", which landed 2.675 (as of 13.12.22) document results and therefore provided an extensive base for the research. Furthermore, classic newspaper articles and reports from research interviews were included given the fast pace the industry's progress. Next to this secondary research approach, primary research in the form of qualitative data collection from two unstructured interviews was included. While primary and secondary research built the basis for the first part of understanding traditional recycling and its inefficiencies better, primary research interviews were used to create the practical case study section. Based on the conducted research, it was found that maximizing the life of LIB by applying circular economy principles is essential for further electrification. Additionally, the central research gap of applied business solutions of innovative LIB upcycling was identified. Deducing from that research gap, the research question: "How can technological innovation compensate for recycling inefficiencies of lithium-ion batteries while building a business case?" was formulated.

## III. Case Study: Overcoming Recycling Inefficiencies

### IV.1 The Need for Innovation

As per Andrew Abbott, a physical chemist at the University of Leicester, "The current method of simply shredding everything and trying to purify a complex mixture results in expensive processes with low-value product" (Hirschlag, 2022). Due to these suboptimal processes, the costs are currently higher to recycle LIB efficiently than to mine more lithium (Oberhaus, 2020). Furthermore, the current battery ecosystem clearly lacks innovation and large-scale, cost-efficient ways to recycle LIBs as globally, only 5% of LIBs are recycled, leaving 95% to waste (Woollacott, 2021). Having developed momentum in Europe's startup scene with various articles in startup magazines and podcasts formats such as deutsche-startups.de, CleanElectric – podcast, Tech & Trees podcast or Startup Corner, the startup Circu Li-ion was chosen to be analyzed more in detail

(Circu Li-ion, 2022). Not many other companies promise to provide an innovative solution to problem of recycling inefficiencies while presenting the potential for long-term business growth.

## IV.2 Company Profile

Circu Li-ion S.A. is a startup founded in October 2021 in Luxembourg and has developed a proprietary battery cell upcycling process that can recover up to 80% of end-of-life battery cells and components aimed at creating an ecosystem of reuse (appendix K.III). The business team is based in Berlin, and the developed process machine operates close to Karlsruhe, Germany. Due to lower costs and emissions regarding logistics as well as contacts through participations in German acceleration programs like ScaleUp Landing Pad Hamburg, Germany builds the first major market for Circu Li-ion (Wiesböck, 2022). This ultimately adds value to the sustainability of the German battery ecosystems and is therefore an applicable case for the German scope of this work. Circu Li-ion's technology begins where the life of LIB ends. That is generally the case when the respective battery pack has lost 20% of its original capacity dropping below a state of health (SoH) of 80%. This generally accepted retirement criterion was first introduced in 1996 and has been the standard for most batteries since then (Zhu et al., 2021). Nevertheless, it is essential to highlight that depending on the battery pack, it contains varying amounts of battery cells. That means that the battery packs' SoH is just an average of battery cells with different SoHs (Kohll, 2022).

## IV.3 Product: Automated Battery & Cell Upcycling Technology

To provide a better understanding of the innovation and how Circu Li-ion aims to overcome recycling inefficiencies, the following describes the product in detail.

Generally, the innovation enables the automated processing of used battery packs and delivers reliable data analytics on each cell. The developed battery cell upcycling process consists of a machine supported by artificial intelligence. When EoL LIBs arrive at Circu Li-ion's facility, they automatically run through four different steps within the machine. First, entire battery packs are pre-diagnosed. Here, batteries are discharged, and their battery state is assessed by artificial intelligence. Secondly, battery packs are automatically opened using robotics and computer vision followed by cell block extraction. Thirdly, the battery cells are disassembled and extracted from the opened battery pack. After the disassembly, the state of health of each individual cell is measured, integrated into the database, and sorted as per SoH and cell type. Having diagnosed and sorted each battery cell, cells with a high SoH (> 90) can be reused and integrated in second life applications like energy storage solutions (Kohll, 2022). Those, EoL cells could lack speed making them not usable for mobility applications. Nevertheless, they are still usable for energy storage systems. Using them for that application omits that new resources are used and that functioning cells are discarded before having unfolded their full potential (Haram et al., 2021). This presented recycling approach can give >80% of otherwise recycled cells a second-life reducing operating cost by >30%, whilst doubling the battery lifetime and reduce $CO_2$ emissions by 80% (Kohll, 2022). The presented steps lead to the following value generation: Reuse of diagnosed cells for second-life applications, more efficient recycling of end-of-life cells and clean recycling of the rest of battery materials (appendix K.IV).

### IV.4 Competitor Analysis

To highlight the unique selling proposition (USP) of Circu Li-ion, three major competitors are analyzed with a descriptive analysis. For that purpose, no detailed comparative analysis or framework is conducted as this analysis focuses on innovation and market positioning. Thus, companies are described according to a short description, process automation, key area, USP, and country they are active in.

First competitor with respect to the use case and technology readiness level is Posh Robotics. Posh Robotics, founded and active in the USA, built a technology that can automatically disassemble battery packs making used lithium battery cells available for second-life applications. Their focus is on disassembling and recycling EV batteries no matter which type they belong to or from which manufacturer they were initially produced. Posh Robotics is also a startup that just raised a 3,8 million USD seed round in June 2022 to further develop their technology (Posh Robotics, 2022).

The second competitor is Vertical Values, which was founded in Germany and is mainly active in Europe. Vertical Values focuses on extracting and repairing used LIB cells. Afterward, cells can be repurposed for second-life applications. Vertical Values' process is manual, while their USP is also to offer logistic services to collect and transport batteries (Vertical Values, 2022).

The third competitor to be mentioned is Nowos. Nowos was founded in 2019 in the Netherlands and focuses on offering all services related to the circularity of the LIB ecosystem, mainly in the Netherlands. That includes battery repairing, consulting services and logistics as well as legal and LIB handling trainings. Furthermore, Nowos tries to establish a collection point ecosystem. So far, there is one collection point close to Amsterdam. Their LIB handling process is manual and focused on repairing (NOWOS, 2022).

While all companies have similar approaches, Circu Li-ion is the only one with a fully automatized LIB disassembly process going down to the cell level with a focus on micro mobility batteries in Europe. Furthermore, Circu Li-ion digitalizes each battery cell with the aspiration of building the largest library of battery types and data base for used cells. These characteristics build the core of Circu Li-ion's USP (appendix K.V).

### IV.5 Go-to-Market Strategies and Business Model

In order to grasp how big the market opportunity is and how markets can be opened in the space of circular economy, the market and Circu Li-ion's business model strategies are analyzed.

Market sizing is presented in USD as the global lithium market is determined in USD by the lithium pricing agency Benchmark Mineral Intelligence. Looking at the market size, the total addressable market can be viewed as the global lithium cell level value. Deriving from Benchmark Market Intelligence, this market can be assessed at 100 billion USD. The serviceable available market corresponds in that regard to the value of reused cells, which is set to be 5 billion USD (Benchmark Mineral Intelligence, 2022). The company is confident in acquiring 10% of the serviceable available market as serviceable obtainable market. That would correspond to a 500 million USD market opportunity (Wiesböck, 2022).

Circu Li-ion aims to enter this market with three different business models. The first two of those are already established and operative as current business models. The first step is a "Machine-as-a-service" (MaaS) model, where Circu Li-ion rents its machine on a subscription base to customers willing to pay for the service of battery disassembly and diagnosis. Here a certain number of batteries is included in the package, and the customers must pay extra for an upgrade when exceeding this amount. The second business model is a "service only" model that is offered to clients, who do not have a big number of batteries, but rather want to create pilot projects, where Circu Li-ion treats the batteries at their facility in Karlsruhe, Germany for them and sends back the second life cells. To put those two business models into context, the first step for customers should be the "service only" model to test and establish pilot projects. With growing quantities, it will be essential to switch to the MaaS business model. The final step is the licensing model aiming for rapid global scaling. Here, customers can lease the technology and establish sites around the world, paying a license fee (Wiesböck, 2022).

As assessed by Wiesböck, the "service only" model will not be lucrative enough long-term but can only be a short-term customer acquisition strategy. In the long-term, MaaS must successfully be implemented in several locations all over Germany. That is the only way logistic costs and $CO_2$

emissions for transport can be kept low even when scaling and acquiring more customers. Having proven the MaaS to be successful and feasible outside the pilot machine in Karlsruhe, the licensing model will be essential to enable a long-term, scalable and profitable business case.

Regarding scaling, Circu Li-ion knows scaling a hardware solution rapidly is rather difficult. Therefore, the hardware is seen as the fundament of building the software solution on top. That way, higher scalability can be reached. Circu Li-ion's long-term vision in that regard is to create the most extensive library for EoL batteries. This scalable software consists of the battery library with continuous addition of battery types, a diagnostic software able to analyze the remaining useful life of each battery cell, as well as cell data collection aimed at creating the largest used cell database (Wiesböck, 2022).

## IV.6 Customers and Revenue Streams

Circu Li-ion has three major areas of customers. The first category are micro-mobility providers like companies offering e-scooter or e-bike rental. Circu Li-ion adds value by disassembling and diagnosing their EoL batteries and sending back cells with high SoH. Also, pilot projects, like the creation of energy storage solutions by external provides are in development. Micro-mobility providers were identified as their batteries are the first ones to reach end-of-life. Thus they have access to the highest number of batteries available. Therefore, this is the segment with the highest market readiness. Furthermore, the USP of most micro-mobility provider is their sustainability claim, thus looking for solutions to make their entire value chain as environmentally friendly as possible (Wiesböck, 2022). The second category are battery producers, who see the value in guaranteeing a fully circular economy for their produced batteries. With the data gathered by Circu Li-ion's software solution, they can increase the efficiency and durability of their batteries. Furthermore, they can first showcase their commitment to CE. The third category are traditional recyclers, which save resources by Circu Li-ion's sorting of EOL batteries. This is because recyclers are obliged to guarantee increasingly a higher purity of their recycling (Kohll, 2022). Therefore, pre-sorting and pre-diagnostics have become a requirement for traditional recyclers, who, at this point, do not have the respective infrastructure (Stena Recycling, 2022). Furthermore, they can be sure to only recycle LIBs with such a low SoH that they cannot be used for second-life applications, thus adding real value to the ecosystem instead of destroying valuable resources (Wiesböck, 2022).

Circu Li-ion has a pricing strategy that consists of five different building blocks. Depending on the service the respective customer group uses, they are charged per service per battery pack or kilogram. Every customer must pay a fix pilot set up cost fee. Secondly is the variable cost of price disassembling and diagnosing on a battery pack level. Third block is the data report to be charged separately. Fourth block consists of the logistics, and the last block is the batching and sorting of diagnosed battery cells. Hereby, the most prominent cost block is the data report (Wiesböck, 2022).

### IV.7 Regulatory Environment

The overall macroeconomic environment is extremely beneficial for Circu Li-ion. Currently, 88% of all batteries are recycled in South Korea or China (Circular Energy Storage, 2021). Especially with Russia's war on Ukraine, Germany, as well as the EU have understood that diversification regarding energy production and consumption is crucial (Umbach, 2022). That builds economic momentum in Europe, and businesses like Circu Li-ion are likely to benefit from it. Furthermore, the regulatory environment is in favor of battery upcycling technologies. Firstly, the EU proposed the new battery pass aimed at protection, conservation, and improvement of the environment by reducing the negative impact of batteries and accumulators and waste batteries and accumulators. It also provides a harmonizing of requirements of batteries and accumulators placed on the internal market applicable to all types of batteries. This regulation proposed to the European parliament and council concerning batteries and waste batteries repealing Directive 2006/ 66/ EC and amending Regulation (EU) No 2019 / 1020 also sets provisions on labeling batteries and their removability from the equipment as well as gives responsibility to producers to take care of the waste management of batteries along the full life cycle. Nevertheless, this directive is currently under revision as new battery types are emerging and complexity increases. So far, it doesn't include batteries for e-scooters and e-bikes, which have rising popularity, but is announced to do so (European Commission, 2020a). Furthermore, the EU formed a battery alliance and pushed for normed batteries and recycling quotas to accelerate recycling in Europe (Hoppe et al., 2021). More favorable legislations include the EU supply chain act requiring companies to carefully manage social and environmental impacts along the value chain (European Commission, 2022a). That is also in line with the Corporate Social Reporting Directive aimed at bringing more transparency into large companies by obliging them to report their management of social and environmental challenges (European Commission, 2022b). Lastly, the EU plans to ban all non-electric vehicles from 2035. causing more and more LIBs to come on the market, eventually requiring end-of-life management at some point (Taylor, 2022).

## V.8 Obstacles to Growth

Looking at internal risks, Cecilia Wiesböck sees threats in losing the focus of product development and commercialization strategy. As Circu Li-ion is an early-stage startup and has several use cases and customer segments, it must make sure to focus on one business model to clearly develop its USP instead of trying to serve a wide range of customers (Wiesböck, 2022).

Regarding external obstacles, Wiesböck sees the risk that many customers won't invest in the sustainability of their value chain if they are not regulated. That counts especially in the current macro environment of recession, where most companies are highly cost-sensitive and hesitant with investments. Another potential obstacle is funding to scale the business. Especially when it comes to grants and funding by the government, the procedures are not in favor of startups like Circu Li-ion. After getting grants or funding from governments approved, it can take several months for startups to receive the transfer (Wiesböck, 2022). This ultimately affects the cash flow, which is, according to research by U.S. Bank, the reason why 82 % of startups and SMEs fail (Flint, 2020). But it's not even the time gap that forces start-ups to finance their expenditures, also the processes of applying for and receiving the money from the government are complicated and therefore capacity binding (Wiesböck, 2022). Additionally, Circu Li-ion is also dependent on recruiting problem-solving and motivated employees with the motivation to change the world. Generally speaking, to solve the problems of our time, skilled individuals must be empowered for entrepreneurial endeavors to take the academic experience into practical application to create business models and have a real impact. Here, as per Kohll, the public and private sectors must create and support even more startup ecosystems where individuals from various backgrounds can come together and build businesses. The support can be financial and non-financially with network and knowledge but should in any case be accessible and unbureaucratic (Kohll, 2022).

### IV.9 Critical Reflection and Limitations of Circu Li-ion's Potential

Even though the startup Circu Li-ion has developed a highly promising technology and is so far successfully building a business case around it, the findings of the study must also be reviewed critically and put into context. According to several statistics, about 90% of new startups fail. (Howarth, 2022). The remarkably high failure numbers are a result of different hurdles such as costs issues, regulatory challenges, bad timing, team issues, as well as no market need and getting outcompeted. Nevertheless, the top reason, with 38%, is running out of cash and the failure to raise new capital (CBS Insights, 2021). That statistic is especially interesting when considering the current environment of rising interest rates and a downturn in global economic growth (Abdulla, 2022). Just at the end of May 2022, Y Combinator, one of the world's largest startup accelerators, advised their portfolio companies to "plan for the worst" and that if they plan to raise money in the next six to twelve months, they might be raising in the peak of the downturn (Singh, 2022). Being a hardware-driven company, R&D processes and technological enhancements are highly cash-intensive, which increases the importance of funding even more.

Apart from funding, Circu Li-ion faces other challenges. While they have already proven a product-market-fit with various paid pilot projects and a full sales pipeline, vertical and horizontal scalability might become an issue for the young venture. Firstly, adapting the machine to other types of battery packs such as batteries from EVs is connected to R&D and cost intensity. Secondly, even though Circu Li-ion tries to solve hardware scaling issue with the described software layer, establishing new sites with hardware is significantly more complex and cost-intensive than it is for purely software driven companies. Another limitation is related to the Battery Directive 2006/ 66/ EC, which does not micro-mobility applications, due to their novelty, yet. Even though it has already been announced by the EU that they will follow, there are so far no concrete guidelines and recycling quotas for them. That causes respective companies to be hesitant about how to treat EoL batteries and decreases the market value for companies like Circu Li-ion at this stage.

The critical reflection of having analyzed the company, therefore, points out that even though an innovation has been developed, the startup faces many challenges making to early to state whether the technology will prevail.

This section gave insights into one startup trying to solve the underlying recycling inefficiencies of LIB. Nevertheless, looking at only one company limits the generalizability of discussions and recommendations. Furthermore, the study mainly targets the 9 Rs connected to extending the lifespan of products and its parts. Namely Reuse, refurbish, remanufacture, and repurpose. Repairing was only briefly touched on in the competitor analysis, but not discussed in detail. The first three Rs (refuse, rethink and reduce) were only implicitly touched as the software layer of Circu Li-ion aims to improve the production of batteries by making them more efficient. The last two Rs (recycle and recover) were rather discussed from a critical standpoint, with the key message of traditional recycling not being the solution for the LIB ecosystem.

## IV. Conclusion and Recommendations

Even though Circu Li-ion is a young startup, it has already managed to disrupt the battery ecosystem. Regulations and international laws are currently in favor of climate tech startups related to CE. Nevertheless, it is too early to tell whether Circu Li-ion and its innovative technology will manage to prevail and scale internationally. On a broader scale, the case study of Circu Li-ion shows that there is a way to realize technological innovation in the context of LIB recycling while building a solid business case. Circu Li-ion in that regard, represents the entire green tech start-up sector accelerating the green revolution by identifying and solving today’s problems. That is done through extensive R&D and entrepreneurial endeavors. In that context, it was found that motivated individuals are needed. That’s why it is important to create even better startup ecosystems where talent is assembled. The climate crisis can be mitigated by getting talent out of the academic context into the practical, entrepreneurial world. Next to that, governments need to support those companies more with unbureaucratic and fast financial resources. That counts especially for asset-intensive hardware solutions, which are needed for some of the biggest climate issues of our time that cannot be solved with software. Minor mistakes in developing hardware pilots can be devastating for start-ups that only have limited financial resources at their disposal. This study also showed the importance of partnership as collaboration along the value chain and integration of government regulation is essential to enable a sustainable battery ecosystem.

Relating to the identified research gap, the request of the literature towards the economy to develop and commercialize innovative, green, and automated solutions for battery recycling has been investigated with this case study. Indeed, traditional recycling cannot mitigate the climate crisis, but technological disruptions such as Circu Li-ion’s have the potential to do so.

# 6 Discussion

The background section highlights the positive impact of the energy transition (ET) and the implementation of a circular economy (CE) on a sustainable future while also addressing their shortcomings. The unification of the ET and CE was dominantly targeted in academic literature from the perspective that CE must be embodied in its full scope in the ET. This is in accordance with this study's hypothesis.

The most important justification for integrating a CE into the ET is framed by the reliance on critical raw materials (CRMs) to produce clean energy technologies. CE presents the excellent potential to mitigate this risk by feeding materials back into the system instead of wasting them. While the literature largely agrees on the theoretical possibility of the CE framework for a sustainable energy system, numerous limitations of a practical implementation are addressed. These comprise recycling inefficiencies, technological backlog, cost issues, and a lack of mindset acceptance. Furthermore, CE currently encounters physical limits in refeeding materials in practice. Given those physical limits, implementing full circularity of materials and products is mostly only feasible with significant losses in quality. As current ambitions to approach full circularity are additionally very energy intensive, the literature also addresses the urgency of a shift to renewable energies (RE) to generate green power for the energy-intensive CE and make the value chain sustainable. In the long run, the CE framework is to be integrated into the context of RE and consumer-driven products in sectors like fashion, packaging, and construction. It can be concluded that the unification must occur in both directions, evidencing that implementing a CE in the German ET enables a long-term sustainable energy system.

The CRM supply dependencies for clean energy technologies further imply a reliance on a few resource-rich countries, which could lead to supply chain and geopolitical risks that will significantly increase CRM prices. To mitigate economic exploitation and manage the diversion between increased demand and diminishing reservoirs, one solution is to promote technological improvements to extend the lifespan of RE technologies and thereby mitigate material demand through a less fast-moving circulation of CRM. To boost resilience and prevent the vulnerability associated with CRM supply chains, the EU currently discusses the EU raw materials act, which aims to identify partners along the supply chain strategy and to prioritize mining and recycling capacities in Europe, which will impact Germany (Noyan, 2022). A lower degree of raw-material input intensity could also be achieved through innovation to reduce the demand for CRMs for each technology, for example, through the re-think CE principle. Furthermore, it is widely agreed upon that recycling should be adopted in every product lifecycle to manage earthly resources better. However, the cost of CRM recovery currently exceeds import costs from mining countries (Vallentin, 2022). Unless financial incentives exist, it is unlikely that the pace of transition to more widespread recycling will increase. Furthermore, there are concerns as to what extent higher recycling rates will reduce primary demand since the need for CRMs seems to continue to grow. To create change that could scale up long-term, greater ambitions toward secondary production are crucial. In addition, a mindset shift for all stakeholders along the value chain is fundamental to enable further CE integration. That also includes national and transnational governments as well as end-consumer behavior.

The challenge of reliance on finite resources becomes particularly evident in the cases of wind, solar, and battery technologies. It is obvious for all three units that the recycling process is disproportionately targeted compared with the other R-principles, which are rather underrepresented. This is despite recognizing that recycling should only be addressed as a last resort when the other R-strategies were not employed. The remaining Rs should be given more attention in the literature, as they have proven their significance in theory and practical CE application in other parts of the economy.

The main problem with the applicability of CE principles in the wind and solar energy technologies lies in need for waste management structures covering the infrastructure to collect the accruing waste that must be further recycled and in the limited capacity of recycling facilities. Per German law, the manufacturer of PV modules and the wind plant operator are responsible for adequate disassembly and recycling. In theory, the responsibility of the collection process has been defined, however, due to low market maturity, the practical execution needs to be improved regarding economies of scale, financial incentives, and predictability of EoL components. Therefore, the supply chain still needs to encompass the entire lifecycle assessment. This incomplete lifecycle assessment is rooted in the lack of government incentives and regulations, as shown in the background research on Germany's CE and ET policies. The "Erneuerbare-Energien-Gesetz" (EEG) contributes to financially incentivizing solar and wind energy technologies and, therefore, pressures a quick approval and fast-paced roll-out. Contrary, adequate enforcement to target the disassembly of clean energy technologies is still deficient. This one-sided approach on behalf of the government can be explained through the need to accelerate the ET. However, the long-term consequences and CE potential must not be ignored, or new challenges will emerge. It raises the question of to what extent the market will self-regulate, but the problem should be tackled now while it is still manageable. Although there are already some approaches to integrate a CE in solar and wind energy, the numbers of publications also show that the topic has not yet found a strong presence in the literature. By contrast, biogas is inherently connected to the CE principles as this power source functions by recycling organic waste. The emergence of biogas is linked to prioritization, and attention to the CE as the generation process is aligned with its principles. However, compared to other energy sources, there is a lower contribution to the energy mix due to a lack of economic viability.

The cluster of batteries, another significant dimension of the ET, can be categorized as a risk for e-waste. The harmfulness of e-waste has already been recognized before dealing with the waste from REs. As a result, its' product lifecycle from design to consumption and recycling structures is already facing greater prioritization than solar or wind energy technologies. Therefore, considering the full lifecycle of batteries is already further ahead but still holds a relatively low degree of current recycling rates. Another challenge is the increasingly diversified scope and portfolio of different battery types that face different product lifecycles and recycling approaches. On the one hand, there are already determined recycling rates for e-waste, but, on the other hand, due to the novelty of mobility technologies, there are no clear targets yet for EVs and micro-mobility. Furthermore, the literature points out that current recycling processes are inefficient, resource intensive, and connected to high $CO_2$ emissions.

The increased development and introduction of AI and smart data management are key tools to approach CE. As with every other dimension, the ET cannot avoid the adoption of digitalization in its scope as it holds significant impacts for increasing efficiency. AI can contribute to the anticipation of production, demand, and waste capacities and result in improved resource management. However, to achieve this maximum yield of efficiency, structured data communication through a decentralized approach is required, which still faces challenges in its infrastructural implementation. This data integration demands more transparency to deduct diagnosis on performance and potential modeling on second-life applications of batteries and other e-waste. This degree of transparency underlies effective stakeholder management working toward the objective that AI must target waste mitigation approaches in the context of CE.

The analysis of the regulatory environment revealed that implementing policies is critical to incorporate a CE in the ET and increase both of their efficiency. While the ET, including its' concept and targets, is already mainly researched, and publicly understood, the CE still experiences vague targets. However, policies are needed that complement both ideas; only in unison, a sustainable ET will be achieved. Policies often address market dynamics that allow legislation to be further scaled and implemented. Therefore, the focus should not lie on policies that act on chance but on incentivizing the market to push efforts related to CE in the ET. The implementation of policies regarding recycling measures of clean energy technologies also has an impact on the degree of RE expansion. In that regard, governments must balance incentivizing and guiding companies toward more circularity while not hindering innovation. Here, it will be critical to strike the delicate balance of regulatory force for the CE and the attractiveness of adopting RE technology.

To complement the theoretical findings drawn from the SLR, practical case studies in the areas of solar and wind energy, as well as battery recycling, EE, and emission-free energy sourcing, were conducted, resulting in further critical insights for the hypothesis. Consistent with the SLR, it was found that climate change and the resulting urgency for the ET require technological innovations. While the market ecosystem must provide the right frameworks and incentives to nourish the development of start-ups and innovation on behalf of existing companies and organizations. This range of innovations covers technical and efficient recycling methods and novelties of business models, infrastructure, and sourcing concepts. New emerging, innovative concepts such as Product-as-a-Service show the economical adaption to new problems and requirements for flexibility. The acknowledgment of technical innovations brings the question of how these novel introductions can be scaled and widely implemented, whereas funding is the primary concern. This challenge occurs mainly due to the reluctance towards hardware-based investments and the preference for software-based investments. However, facing today's problems requires hardware-based innovations, like battery recycling, innovations for clean energy technologies, and the expansion of these technologies in-country or overseas to sustainably manage the CE in the ET.

This demand for hardware innovations and the wide scaled roll-out is empowered and tied to research in technical universities, whereas entrepreneurial endeavors must be laid and incentivized to convert technical abilities and research into practical business use cases. Despite this pressing need for hardware, it was found that companies developing these solutions face major obstacles regarding product engineering and funding.

Firstly, the R&D process is significantly more cost-intensive, given the development, production, and procurement of hardware components. Furthermore, receiving governmental funding on the European or national level is very complex and only transferred to the respective company after the investments have been carried out, and bank loans come with a high personal risk. This ultimately results in cash flow issues, as guaranteeing liquidity is critical for a startup. Thus, it should be considered to distribute funding less bureaucratic way and beforehand. Furthermore, the current structure of VC funding can be questioned, given that VC companies tend to prefer highly scalable software solutions and are somewhat reluctant with cash-intensive hardware solutions. Lastly, there must be a change in the return on investment, as it should encompass not only financial returns but also social improvements, long-term effects, and the degree of contribution of CE in the ET, as is demonstrated in the MENA clean energy expansion case.

Another critical finding evolves around partnerships and the collaboration of different stakeholders, which is integral for accelerating the ET. It was found in the practical case studies that even for sustainable products, only some of the value chain is sufficiently integrated into designing processes, so products lack efficient EoL solutions. Through the missing exchange between different stakeholders, problems are being solved at one stage but new ones are created at different stages. Sharing knowledge and including partners from the beginning can thus decrease issues around the later stages of a product cycle. These partnerships can also be transferred on an international level. Encouraging projects in other parts of the world and sharing technical knowledge can help foster regional prosperity and employment rates while simultaneously advancing the ET. Progressive employment is another opportunity for every country to foster entrepreneurship and the development of startups. Eventually, circularity is a global topic necessitating global and entire value chain problem solving, including as many stakeholders as possible. In an ideal world, partnerships and governmental incentives make CE principles in technology more feasible than technologies and business models based on fossil fuels and thereby approach SDG 17 – partnerships for the goals.

Lastly, the discussion can be directed towards thought leadership and setting a role model. It was found that many companies, as well as end consumers, need to be made aware of circularity issues in their respective industries. Taking recycling as an example, it was found that it is generally perceived as something positive, although there are high inefficiencies in its current state, and therefore, constant innovation and improvement are required. As companies focus mainly on recycling, other R's from the CE framework, such as reuse or refurbish, are neglected, leaving room for business models before the process of recycling. Companies disrupting the market must overcome the positive perception of recycling to emphasize the added value of their innovation, demonstrating efforts for thought leadership.

Other companies promoting CE through their business model might not be aware of it and are therefore not broadcasting their positive influence. Highly developed countries like Germany are responsible for leading the way, pioneering with technology and funding, and sharing their knowledge so that CE concepts can be implemented globally. Lastly, this study revealed that all stakeholders must be integrated to approach circularity in a part of the economy. That counts for public institutions such as government and universities as well as private companies such as corporations, investors, and startups. Moreover, general consumer behavior and societal pressure significantly influence the demand for sustainable products and the enforcement of regulations.

# 7 Limitations and Future Research

The scope of the study encompasses the relationship between circular economy (CE) and the energy transition (ET) and investigates the possibility of CE posing a solution to a sustainable energy system. Due to this scope, various limitations are in place related to constraints that limit a more comprehensive execution. Firstly, the selected search term combinations do not portray all conceivable possibilities in the systematic literature review (SLR). A more adequate execution was not pursued due to the time constraints of the study processing time. Although the search records were expanded with interchangeable synonyms, this expansion still needs to be completed to represent the full scope of the research body. Given the breadth of topics that relate to both concepts, especially the ET whose conceptualization is somewhat older than CE, some additional topic areas may have yet to be considered. Further research targeting additional search terms could lead to a better understanding beyond the insights of this study.

Another limitation of the SLR is that only one database was searched, which holds future research potential to add further databases that could expand the data output. However, Scopus was chosen as it is an extensive database of peer-reviewed literature, for example, compared to the Web of Science, that also indexes a variety of "grey" literature (Gregorio et al., 2018; JMLA, 2016). Furthermore, since the categorization of articles and the determination of their areas and findings depend on the authors' subjective judgments, the analysis may be prone to researcher bias. This limitation is also transferable to the definition of the inclusion and exclusion criteria determining the incorporation for further review, which also impacted the hypothesis deduction.

To complement the academic investigation with data from Scopus, five market case studies were depicted to portray current market evolvements. Here, the limitation occurs that the selection of the market and resulting research institutes and companies dominantly target the German market.

A broader consideration of European research and market motions as well as academic publications, could complement a full review of the study.

Another limitation was created through the data collection method as the qualitative interviews, although serving as a vital input source, cannot account for statistical validity and represent only a small sample from which generalizations were deducted. Furthermore, the research could be complemented by investigating the practical implementation of the CE in ET in topics in addition to the five selected ones, for example, biogas or green hydrogen. The study attempted to grasp a broad scope of the underlying sub-topics concerning the integration of CE in ET. However, it is not fully exploited, and there is space for further investigation. Finally, the explorations of the sub-RQs were qualitative, so no quantitative analysis was done. For example, when assessing the relationship between the two concepts in sub-RQ1, an impact assessment would increase the accuracy of the results and should be considered in future research.

# 8 Conclusion

This study aimed to investigate whether and how the circular economy (CE) framework can be integrated into the German energy transition (ET) to build a sustainable energy system. The hypothesis was confirmed by conducting a systematic literature review (SLR) to pinpoint the research gap, assess the status of the CE integration, and understand where its’ potential and limitations lie. Furthermore, analyzing current market developments of different industries and projects provided further insight into the practical contribution of market participants to adopting circularity concepts and further affirmed the hypothesis.

It was found that to build a sustainable energy future, the ET should encompass the CE framework within various parts of the economy. The primary objective appears to be scaling the expansion of REs in Germany. However, at present, End-of-Life scenarios are often not sufficiently considered in the initial design of their technologies resulting in unprecedented volumes of energy-related waste.

Additionally, critical resource materials (CRM) are inevitably interlinked with the manufacture of RE-related technologies. The associated price volatility, import dependency, and ET insecurity of Germany can be mitigated through CE. However, it was recognized that some CRM exploitation and import is inevitable and that the focus must also lie on extending their lifetime and increasing efficiencies within the cycle of their application to the maximum. As the cases have shown, this can be achieved either by disrupting the market with innovative recycling technologies or by increasing the efficiency of existing technologies to maximize their lifetime. While it is necessary to reduce CRM import dependency and to manage waste, it was also shown that Germany still relies on an import strategy to counteract supply volatilities and the lack of storage capabilities. The study invites to view the integration of the CE framework in the ET in the bigger picture; alongside applying the ten R-principles to physical products, more efficient technologies and consumption of resources and energy will be integral.

Furthermore, importing RE from other countries with higher emergence of solar and wind serves to diversify Germany's green supply strategy to guarantee the security of a consistent, sustainable energy supply. In that regard, it is a recurring theme that collaborative partnerships are needed, and technological innovation must be fostered since, as outlined in the challenges of CE, the main task in the ET will lie in avoiding an intrasystem shift of problems. However, CE practices must be implemented across the German borders, whereas Germany serves on the one hand as a role model to implement CE on its own. On the other, the country is responsible for addressing the need for CE in the countries where green energy is sourced additionally.

Due to the novelty of the topic and the momentum it is experiencing, the study's unique approach of combining academic research with a practice orientation provided a sound theoretical understanding and accurate insights into the latest CE energy solutions in Germany. Therefore, this study presents a valuable addition to the existing body of research. Germany acts as a pioneer and leading example in Europe and on the world stage due to its economic strength and political stability. Assessing the development of the country’s clean energy sector in the literature and in practice emphasizes the importance of incentivizing companies and demanding from politics to enable a CE in the energy sector.

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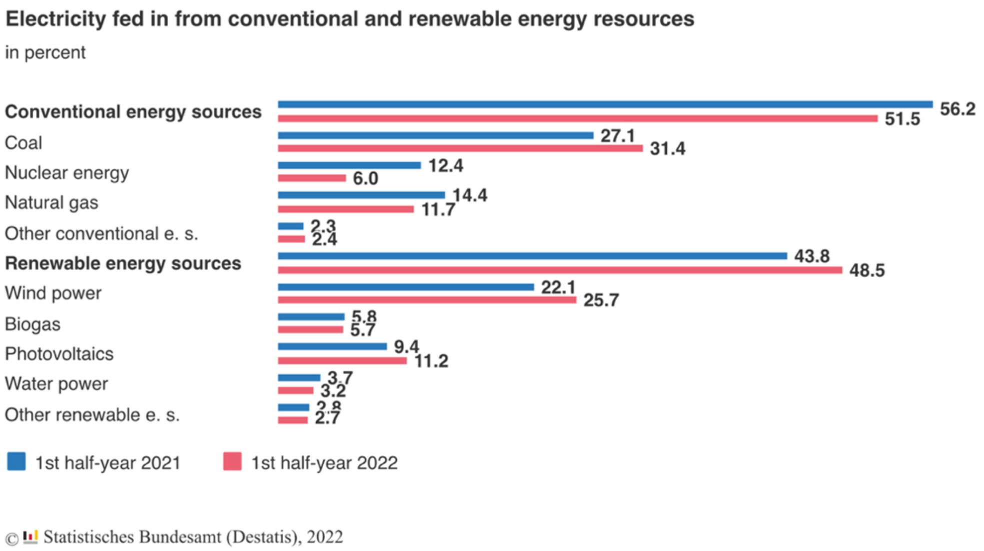
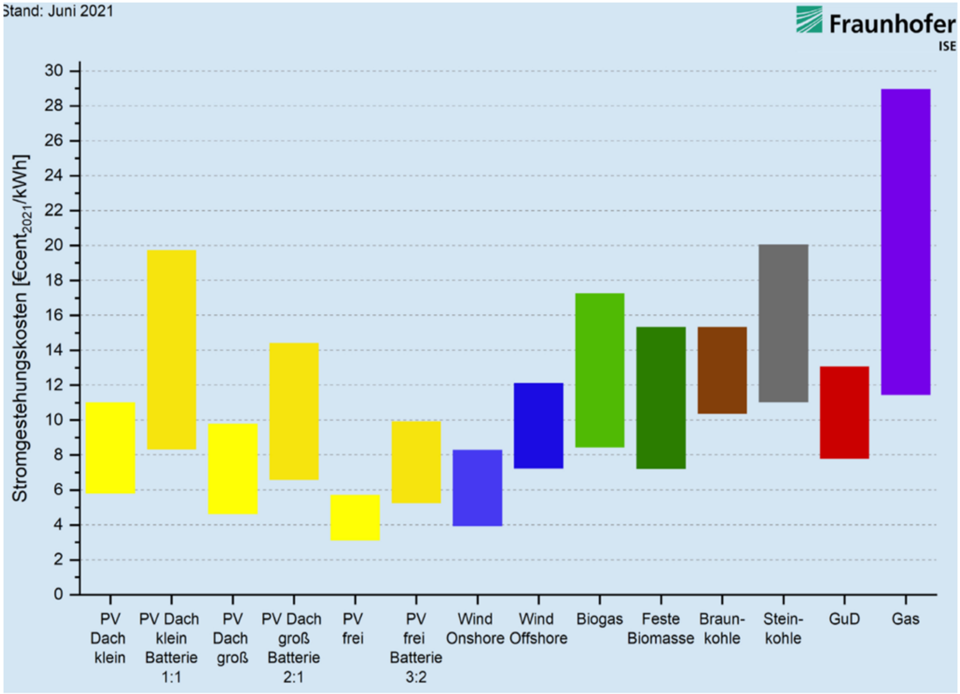
# 10 Appendices

## Appendix A: Energy mix of Germany in the first and second halves of the year 2022



Source: Statistisches Bundesamt (2022)

## Appendix B: Cost of renewable and conventional energy sources in Germany in 2021



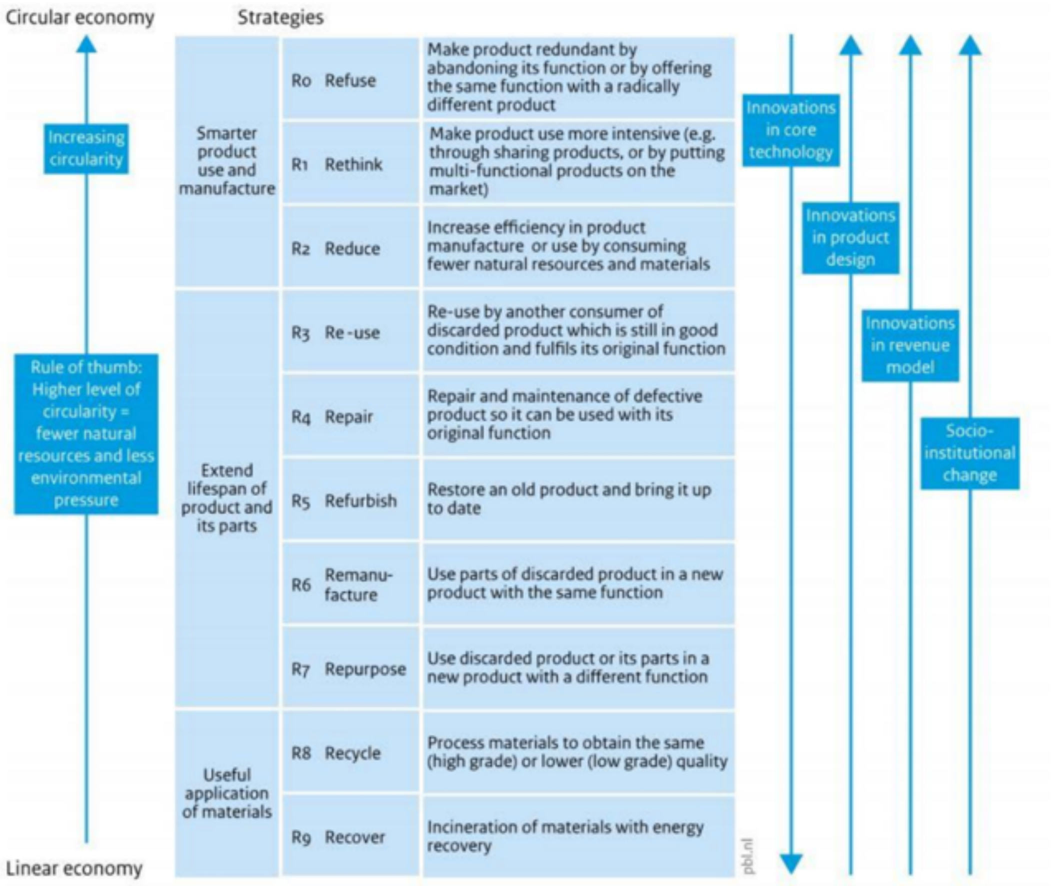
Source: Fraunhofer ISE (2015)

## Appendix C: Materials needed for renewable technologies

| Technology | Materials needed |
|---|---|
| Photovoltaics | Silicon, glass, aluminum, silver, copper, steel, polymers, electronics, indium, gallium, tellurium, germanium, cadmium, zinc |
| Wind turbines | Steel, copper, aluminum, iron, cement, glass reinforced plastics, plastic resins, dysprosium, neodymium, praseodymium, electronics |
| Electric vehicles | Steel, aluminum, glass, copper, metal composites, fiberglass, rubber, ceramics and magnets, polymers, lead acid batteries, lithium-ion batteries, electronics |
| Lithium ion batteries | Steel, iron, nickel, copper, manganese, lithium, cobalt, graphite, zinc, polymers, electronics |

Source: Mulvaney et al. (2021)

## Appendix D: Descriptions of the 10 R's and categorization into respective stage of the CE

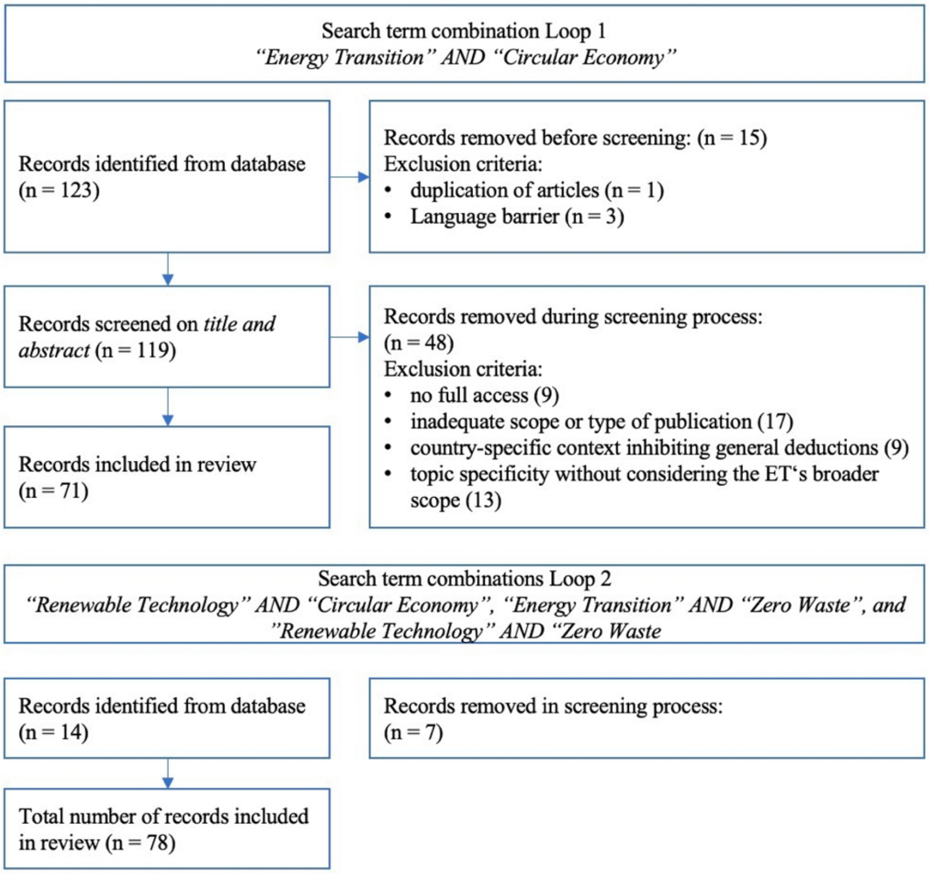


| Strategies | | | |
|---|---|---|---|
| Smarter product use and manufacture | R0 | Refuse | Make product redundant by abandoning its function or by offering the same function with a radically different product |
| | R1 | Rethink | Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market) |
| | R2 | Reduce | Increase efficiency in product manufacture or use by consuming fewer natural resources and materials |
| Extend lifespan of product and its parts | R3 | Re-use | Re-use by another consumer of discarded product which is still in good condition and fulfils its original function |
| | R4 | Repair | Repair and maintenance of defective product so it can be used with its original function |
| | R5 | Refurbish | Restore an old product and bring it up to date |
| | R6 | Remanufacture | Use parts of discarded product in a new product with the same function |
| | R7 | Repurpose | Use discarded product or its parts in a new product with a different function |
| Useful application of materials | R8 | Recycle | Process materials to obtain the same (high grade) or lower (low grade) quality |
| | R9 | Recover | Incineration of materials with energy recovery |

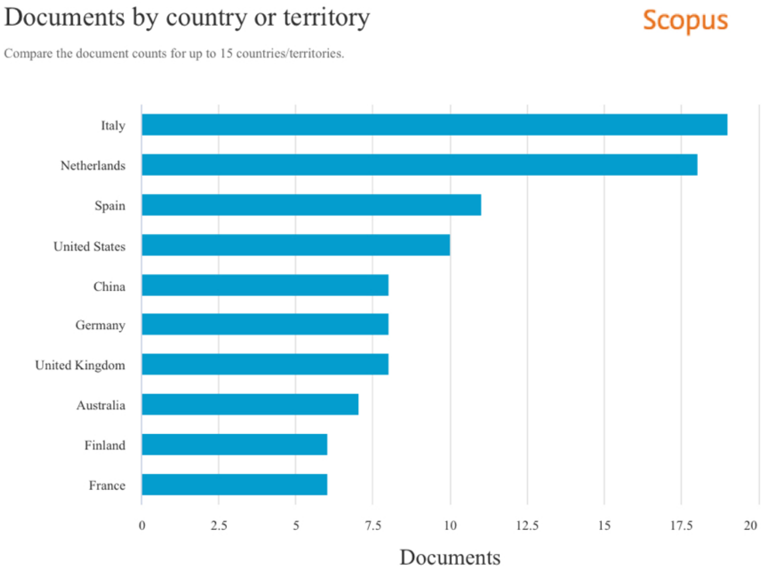
**Source:** Potting et al. (2017), Figure 1 : 5

Source: Potting et al., 2017

## Appendix E: Publication Scopus Search Strategy



## Appendix F: Number of articles returned by the SLR per location of publication



## Appendix G: SLR Sub RQ1 – categorization of articles according to relationship between CE and ET and according to perspectives towards the integration of the two concepts including proof quotes and justifications for the authors‘ decisions.

| # | Title | CE for ET | ET for CE | CE & ET | CE & ET individually | Justification for alignment categorisation | Perspective on integration | Justification for perspective categorisation |
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| 72 | Future city visions. The energy transition towards carbon-neutrality: lessons learned from the case of Roeselare, Belgium | | | | x | ""The decarbonisation scenario presented combines technologies for renewable energy generation, such as PV panels and wind turbines, with innovative solutions of circular economy concerning sewage treatment from cruise ships and algae farms to generate biogas, biofuel and other materials (e.g. fish-feed for aquaculture)." | | None as concepts not integrated in the article |
| 15 | Is technological innovation a driver of renewable energy? | | | | x | "This study unveils the causality between technology innovations and renewable energy in Germany." | | None as concepts not integrated in the article |
| 27 | Setting the European environment and health research agenda –under-researched areas and solution-oriented research | | | | x | "In contrast, this paper identifies key topics and approaches that are under-researched, yet, are critical for the implementation of the EU Green Deal, related strategies and action plans, and require further investigation and investment." | | None as concepts not integrated in the article |
| 121 | Transition thinking and business model innovation-towards a transformative business model and new role for the reuse centers of Limburg, Belgium | | | | x | Article addresses the topics separately: it recognises the energy transition as driver for business model change but also the pressure for a circular economy | | None as concepts not integrated in the article |
| 126 | Two-phase Olive mill waste: A circular economy solution to an imminent problem in Southern Europe | | | | x | "However, the project presented is environmentally viable, since the carbon dioxide emissions that would be released to the atmosphere if the TPOMW were to decompose naturally are reduced by a factor of 7 times. This study thus constitutes an example of a "green and circular economy"." | | None as concepts not integrated in the article |
| 102 | Carbon emission and plastic pollution: How circular economy, blockchain, and artificial intelligence support energy transition? | | | | x | "Though too late, various efforts are promoted by governments and driven by industries to rapidly decarbonize our energy systems and sustainably consume and recycle raw materials. We have discussed two ongoing projects in the domain of energy transition and circular economy." | | None as concepts not integrated in the article |

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| 14 | Supply chain risks of critical metals: Sources, propagation, and responses | | | | x | "Thirdly, to respond effectively to the supply chain challenges, there are short-term measures like stockpiling and price hedging and long-term approaches like recycling and circular strategy." | | None as concepts not integrated in the article |
| 55 | An intelligent platform for evaluating investment in low-emissions technology for clean power production under ETS policy | | | x | | "[...] subsequently stimulating a circular economy energy transition." | Potential | "CCS is a reliable option to assist China in mitigating its GHG emissions." |
| 50 | Assessing cobalt supply sustainability through production forecasting and implications for green energy policies | | | x | | Talking about a circular green economy | Potential | "More so for CRMs – which are crucial for contributing to socioeconomic development in the context of a sustainable and circular green economy – the need to ensure supply and sustainability is vital." |
| 51 | Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy | | | x | | "Bioenergy coupled with Carbon Capture and Utilization (BECCU). BECCU is a key enabling technology for the energy transition addressing simultaneously the renewable feedstock-based circular economy." | Potential | Same quote |
| 108 | Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals | | | x | | "In this paper, we develop a method to assess the environmental impacts of metal scenarios. The method is life cycle based [...]." and "For the other metals, the energy transition may have substantial benefits." | Potential | "By far, the most effective option for all metals appears to be to increase the share of secondary production. This would reduce emissions, but is expected to become effective only in the second half of the twenty-first century." |
| 61 | Green hydrogen-based pathways and alternatives: Towards the renewable energy transition in South America's regions – Part A | | | x | | "The results of this research contribute to the renewable, sustainable energy transition and in accordance with the precepts of the circular economy." | Works in practice | "Therefore, as can be seen in Fig. 4, the results found in this research contribute to a renewable, sustainable energy matrix and in accordance with the precepts of the circular economy for the search for new sources of energy and the transition to a hydrogen economy, with emphasis on green hydrogen." |
| 23 | Indicator-based assessment of sustainable energy performance in the European Union | | | x | | "Sustainable energy transition is also a key element of circular economy, social welfare and justice." | Potential | "All EU member states improved their sustainable energy performance between 2007-2009." |

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| 32 | Organizational, societal, knowledge and skills capacity for a low carbon energy transition in a Circular Waste Bioeconomy (CWBE): Observational evidence of the Thessaly region in Greece | | | x | | "Advancing a Circular Waste Bioeconomy (CWBE) should be a priority over business-as-usual, entailing sustainable resource use in early and late stages of industrialization processes." | Potential | "Advancing a Circular Waste Bioeconomy (CWBE) should be a priority over business-as-usual, entailing sustainable resource use in early and late stages of industrialization processes." |
| 33 | Recent advances in the global rare-earth supply chain | | | x | | "[...] significant challenge to the energy-transition strategies and the national security of many countries. This issue of MRS Bulletin delves into the materials science aspects of the REE supply chain, including fundamental REE mineralogy, REE separation and extraction, REE mining economics, the environmental impacts of REE mining and processing, and circular economy potential for REEs." | Potential | "Such an imbalance of the critical metals supply chain poses a significant challenge to the energy-transition strategies and the national security of many countries.This issue of MRS Bulletin delves into the materials science aspects of the REE supply chain, including fundamental REE mineralogy, REE separation and extraction, REE mining economics, the environmental impacts of REE mining and processing, and circular economy potential for REEs." |
| 56 | Simultaneous decarbonisation of steel and Oil&Gas industry by MSW gasification: Economic and environmental analysis | | | x | | "Here the authors studied in detail a possible application of waste to chemical process in an industrial district that would give an important contribute to reduce the carbon dioxide emissions, following the principles of circular economy." | Potential | "The proposed process is based on the circular economy principles because it transforms a waste product in a raw material for a new process." |
| 79 | Situating coupled circular economy and energy transition in an emerging economy | | | x | | "Hence, the current study examined the challenges and opportunities of implementing coupled circular economy and energy transition model in Nigeria." | Potential | "Scaled coupling of CE and ET may occur in two fundamental ways: accelerated low-carbon and RE supply across production and consumption value chain; and transformation of 'waste' from productionconsumption functions to supply raw material and energy services." |
| 128 | The role of renewable energy in the promotion of circular urban metabolism | | | x | | "Constant consumption of resources exerts pressure on the environment not only due to its exploitation, but also because once processed, the resources produce waste, emissions or effluents. Cities are responsible for more than three quarters of the emissions of greenhouse gases. It is anticipated that the urban population will increase by up to 80% by the mid-21st century, which will make the | Potential | "A review of the literature establishes that there are eleven renewable technologies with different degrees of maturity that could reduce the import of energy resources, which would contribute to changing the metabolic linear model into a circular model." |

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| | | | | | | current energy model unsustainable, as it is based on the intensive use of fossil resources." | | |
| 24 | A network of circular economy villages: design guidelines for 21st century Garden Cities | | | x | | "By integrating energy and water micro-grids and a regenerative agricultural system with the built environment, these can be designed to provide the community’s basic needs, including food, water, energy, shelter, plus work opportunities within the village environment. The energy infrastructure can also be designed to power a fleet of shared electric vehicles for movement within and outside the village." | Works in practice | "This section will illustrate how various categories of infrastructure are changing, with the trajectory pointing towards local, integrated, precinct-scale, circular economy infrastructure rather than large-scale, centralised, and linear (one-directional) infrastructure. Significantly, it will be shown that the trajectories of individual infrastructure types are converging, enabling the development of an integrated, systems-based approach to the design of village infrastructure." |
| 48 | Bioethanol from Wastes for Mobility: Europe on the Road to Sustainability | | | x | | "This is the only way to attain the EU targets regarding carbon neutrality for 2050, contributing to sustainability and circular economy." | Potential | "The main conclusions demonstrated that R&D and technological efforts should continue reducing production costs and making ethanol economically more competitive and attractive to investors. Investing in this area will support more technology implementation in the existing industrial plants. This is the only way to attain the EU targets regarding carbon neutrality for 2050, contributing to sustainability and circular economy." |
| 105 | Circular economy and energy transition: A nexus focusing on the non-energy use of fuels | | | x | | "The coordinated circular economy–energy transition approach could bring in synergistic effects, such as promoting circular economy activities among industries, reducing energy demand, and attaining additional greenhouse gas mitigation potential." | Potential | Same quote |
| 60 | Copper and critical metals production from porphyry ores and E-wastes: A review of resource availability, processing/recycling challenges, socio- | | | x | | "In this review, a critical analysis of ore distribution/processing, metal extraction, E-waste generation and E-waste recycling is presented, focusing on identifying challenges and how to address them with emerging technologies and sustainable socio-environmental strategies." | Potential | About how circular economy concepts are becoming more mainstream in the resources sector and recycling methods are being upgraded using advanced techniques |

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| | environmental aspects, and sustainability issues | | | | | | | |
| 36 | Exploring the effects of energy transition on the industrial value chains and alternative resources: A case study from the German federal state of North Rhine-Westphalia (NRW) | | | x | | "Thus, this paper investigates the interlinkages between the energy transition and the transformation towards a circular economy in Germany." and "The analyses prove the inherent interrelation between energy transition and circular economy. On the one hand, energy transition does not only bear various techno-economic challenges and have substantial effects on the production costs, but it also affects the availability of secondary materials." and "On the other hand, circularity approaches can also influence the energy transition." | Potential with limitations | "Besides the intended reduction of GHG emissions and increasing recycling quotas, energy transition and circularity concepts also have unintended effects on material flows." |
| 62 | Financial resources for the investments in renewable self-consumption in a circular economy framework | | | x | | "In addition, the active participation of consumers as producers and the decentralisation of the energy sector also align with the CE framework." | Potential | "Given these premises, this study investigates the financial resources associated with self-consumption facilities in the EU through a case study in Spain as an interdisciplinary analysis in order to bring sustainable energy consumption, zero-emission goals and renew-ables in a CE together in a single research framework." and similar other lines in the text show that the authors perceive the integration to be necessary and achievable |
| 21 | Re-powering the Nature-Intensive Systems: Insights From Linking Nature-Based Solutions and Energy Transition | | | x | | "In the framework of a green and circular economy, NbS can be considered as a reliable source for transiting from traditional carbon-based supply systems to a new renewable-oriented circular economy." | Potential | "However, both concepts have a remarkable contribution to climate change mitigation due to their potential to promote GHG and CO2 reduction as well as ecosystem restoration. Moreover, NbS and ETs are the kind of natural climate solutions by which policy makers and planners can achieve the Paris Agreement goal and sustainability transition notion. In addition, the contributions of this study would pave a new way to the combination of different types of ET and NbS in a time where interlinked social, ecological, and technological innovations require multifunctional and transdisciplinary solutions." |

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| 87 | A heuristic approach to the decision-making process of energy prosumers in a circular economy | | x | | | "A key principle of the circular economy (CE) is that energy is powered via renewable sources [1], leading to significant reductions in fossil-fuel consumption [2,3] and greenhouse gas (GHG) emissions [...]." | Works in practice | Same quote |
| 122 | How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005 | | x | | | "Whereas sustainably produced biomass that is recycled within the biosphere can be an important component of a CE, reducing consumption of fossil energy carriers is necessary to further raise the degree of circularity in the economy. The energy transition from fossil to renewable energy sources is therefore an important prerequisite for moving toward circularity." | Potential | "Although EOL recycling rates for some materials are already high, considerable improvements seem possible. This requires the consistent eco-friendly design of products (including buildings and infrastructures) [...]." |
| 89 | Implementing a new human settlement theory: Strategic planning for a network of regenerative villages | | x | | | "The Circular Economy is underpinned by renewable energy, therefore, taking a systems approach, an energy micro-grid will generate, store, monitor and distribute renewable energy on-site." | Works in practice | "The energy system will power a water system that will be cycled through the site, providing for residents, irrigating crops and watering animals. The living and work spaces will be passively designed to minimise energy demand and more generally, the energy, water, food and built systems will be integrated to maximise efficiency." |
| 86 | Methodology for dimensioning the socio-economic impact of power-to-gas technologies in a circular economy scenario | | x | | | "Innovative and sustainable energy technologies are needed in the transition of energy toward a circular economy. Because of the use of renewable energy and carbon utilization, power-to-gas could be a cutting-edge technology that supports the circular model in future sustainable energy markets." | Potential | "To overcome these challenges and help firms in their transition toward circular economic models, favorable conditions are needed." |
| 95 | SME's, energy efficiency, innovation: A reflection on materials and energy transition emerging from a research on SMEs and the practice of Energy Audit | | x | | | "Attention will be paid also to those obstacles and facilitating factors that are relevant for the promotion of the circular economy-which is also, in fact, a strategy for achieving energy efficiency." | Potential | "SMEs orientations are important for achieving a better knowledge of the cycle of materials, especially in relation to the possibility of directing it towards the pursuit of environmental objectives such as energy saving and the circular economy." |

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| 92 | Steel in a circular economy: Global implications of a green shift in China | | x | | | "China could take advantage of an increasing availability of obsolete steel scrap in the coming decades, moving towards more circular, and potentially greener, steel production" and "Therefore, the increased circularity of steel production needs to be aligned with policies for increased energy efficiency (Hasanbeigi, Morrow, Sathaye, Masanet, & Xu,2013) and energy transition towards low-carbon technologies inChina as well as in other regions to reap the potential environmental benefits from increasingly meeting the future demand of steel from secondary sources." | Potential | Same quote |
| 117 | Towards a closed carbon cycle and achieving a circular economy for carbonaceous resources - Net zero emissions, resource efficiency and resource conservation through coupling of the energy, chemical and recycling sectors | | x | | | "The projected increased reduction in lignite for electricity production in Germany, the need to increase carbonaceous waste recycling as well as the anticipated availability of renewable electricity from Germany's energy transition all point to a high potential for closing the carbon cycle ($C^3$) for the nation's carbon intensive industries. In this article, we present a concept for achieving net zero emissions, resource efficiency and conservation by coupling the energy, chemical and recycling sectors to support a circular carbon economy." | Potential | "To illustrate our concept, results from process model evaluations of domestic carbon feedstock (i.e. plastic waste and lignite) for olefins production in Germany are presented." |
| 76 | Can the 1.5 C warming target be met in a global transition to 100% renewable energy? | | x | | | "This potential phaseout of the global fossil fuel and military infrastructures could contribute an enormous input to a circular economy, recognizing that the full potential of this economy can only be realized with progress towards a global RE supply." | Potential | "More efficient renewable technologies in the near future will make this transition easier and promote the implementation of a global circular economy." |
| 12 | Circular economy principles in community energy initiatives through stakeholder perspectives | | x | | | "This study's contribution falls at the intersection of these concepts, where community energy initiatives provide a platform to integrate CE strategies." and "The study discussed how community energy initiatives encourage responsible consumption and perceive the CE concept." | Potential | "Adopting circular economic practices in community energy initiatives will help leverage the cultural approach favouring circularity." |

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| 54 | Sustainable alternative routes versus linear economy and resources degradation in eastern romania | | x | | | "A linear economy is based on unsustainable mechanisms such as the extraction of raw materials for industry; energy sources based on fossil fuels, water, and soil resource depletion [3,4]; consumer society; and landfill-based waste management systems [5]." | Potential | "The transition to renewables sources is imperative to support circular economy mechanisms." |
| 7 | A Critical Environmental Analysis of Strategic Materials Towards Energy Transition | x | | | | "Global consumption of materials is rising rapidly leading to an increase in environmental impacts associated with the supply chain. Similar issues also affect a set of materials strategic for the transition towards a sustainable energy production and distribution system: i.e. materials employed in renewable energy (wind turbines and photovoltaic panels), energy storage, electrolysers, electricity distribution networks and electric vehicle charging infrastructure." | Potential | "[…], several materials - such as copper, aluminum, nickel etc. - already present high percentrages of recycling rate and recycled material […]." and "[…] specific materials […] and related applications - especially wind turbines for REOs and electrolysers for precious metals - will need to be monitored to allow a scientific development in their recycling process and/or substitution and to guarantee a sustainable transition towards renewable energies." |
| 57 | A framework and baseline for the integration of a sustainable circular economy in offshore wind | x | | | | "However, circular economy is not yet commonly and systematically applied to offshore wind." | Potential | Same quote |
| 71 | A review of Africa's transition from fossil fuels to renewable energy using circular economy principles | x | | | | "This paper reviewed existing literature relevant to Africa's energy transition – whether it is enabled and can be guided by the principles of a circular economy" | Potential | "Obwohl es nur wenige Daten darüber gibt, wie der Übergang durch die Kreislaufwirtschaft unterstützt werden kann, gibt es eine große Chance für weitere wissenschaftliche und industrielle Forschung, die weitere kontextbezogene Unterstützung bieten kann." |
| 8 | Accelerating the Transition to a Circular Economy for Net-Zero Emissions by 2050: A Systematic Review | x | | | | "Achieving net-zero emissions by 2050 will require tackling both energy-related and non-energy-related GHG emissions, which can be achieved through the transition to a circular economy (CE)." | Potential | "Also, results show that CE principles are applied at the micro-, meso-, and macro- (national, regional, and global) levels across sectors with the dominance of the industrial sector. The agriculture, water, and energy sectors are at the initial stages of implementation. Additionally, the use of carbon capture and utilization or storage, conceptualized as a circular carbon economy, needs attention in tackling CE implementation in the energy sector, especially in hydrocarbon-endowed economies." |

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| 9 | Circular economy priorities for photovoltaics in the energy transition | x | | | | "This analysis leverages the PV in Circular Economy tool (PV ICE) to evaluate two circular economy approaches, lifetime extension and closed-loop recycling, on their ability to reduce virgin material demands and life cycle wastes while meeting capacity goal." | Potential | "From the results of our 336 lifetime-recycling scenarios, we find that on a mass basis there are multiple ways to reduce virgin material demands and life cycle wastes while maintaining installed capacity through 2050." |
| 30 | Cleaner technologies for sustainable development | x | | | | "Cleaner technologies are becoming increasingly important on our path towards sustainable development." and "By dissecting recent examples of cleaner technologies in environmental systems, water systems and industrial processes, circular economy principles are obeyed through the application of cleaner technologies, where the material and energy loops are closed through cross-sectoral integration." | Potential | "Cleaner technologies are becoming increasingly important on our path towards sustainable development." |
| 123 | Cleaning after solar panels: applying a circular outlook to clean energy research | x | | | | "These observations reflect the importance of a circular economy outlook in renewable energy system design and call for further research in this area." | Potential with limitations | "We find that annual new waste introduced into the market can exceed the volume of new installations within the next decade, which can more than double the levelized cost of energy for solar generation and jeopardise the cost competitiveness of this technology in the foreseeable future. These observations reflect the importance of a circular economy outlook in renewable energy system design and call for further research in this area." |
| 129 | Closing the low-carbon material loop using a dynamic whole system approach | x | | | | "Circular economy initiatives that aim to institute better resource management practices could exploit these technological commonalities through the reuse and remanufacturing of technology components across infrastructure systems. In this paper, we analyse the implementation of such processes in the transition to low carbon electricity generation and transport [...]" | Potential | "Circular economy interventions such as recycling and reuse of technologies are advocated as solutions that reduce the reliance on critical materials, as well as reducing primary material demand and the associated environmental impacts of their extraction." |

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| 69 | Achieving Sustainable Development Goals in rare earth magnets production: A review on state of the art and SWOT analysis | x |  |  |  | About how sustainable raw earth materials are for wind energy | Works in practice | Same quote |
| 25 | Assessing China's potential for reducing primary copper demand and associated environmental impacts in the context of energy transition and “Zero waste” policies | x |  |  |  | “To conserve resources and enhance the environmental performance, China has launched the “Zero waste” concept, focused on reutilization of solid waste and recovery of materials, including copper. Although several studies have assessed the copper demand and recycling, there is a lack of understanding on how different waste management options would potentially reduce primary copper demand and associated environmental impacts in China in the context of energy transition. This study addresses this gap in view of a transition to low-carbon energy system and the optimization of copper waste management combining MFA and LCA approaches." | Potential | "Under present Chinese policies, reuse and recycling of copper containing products will lead to a somewhat lower dependency on primary copper in 2100 (11187Gg), as well as lower total GHG emissions (64869 Gg CO2-eq.) and cumulative energy demand (1.18x10^12 MJ). Maximizing such “Zero waste” options may lead to a further reduction, resulting in 65% potential reduction of primary copper demand, around 55% potential reduction of total GHG emissions and total cumulative energy demand in 2100." |
| 17 | Assessing the environmental performance of a novel coal mine brine treatment technique: A case in Poland | x |  |  |  | "The recovered solid products provide a circular perspective of treating Polish coal mine wastewater […]." | Works in practice | "The Dębié nsko case study regards a WWTP which treats the brine of the active Budryk coal mine at the Upper Silesian Coal Basin." and "The recovered solid products provide a circular perspective of treating Polish coal mine wastewater […]." |
| 65 | Circular economy for clean energy transitions: A new opportunity under the COVID-19 pandemic | x |  |  |  | "The results indicate that circular economy options, represented by cascading use of industrial surplus heat and electrification of the transport sector, have great potential to facilitate Meili Town’s clean energy system transition" | Works in practice | "By implementing circular economy measures, the improved savings in accumulated (2020–2040) final energy use, CO2 emissions, and PM2.5 emissions could be 7%, 10% and 17% respectively, compared with the new policy scenario which simply implements energy efficiency measures." |
| 104 | Circular economy for the energy transition in Saint Petersburg, Russia | x |  |  |  | "The pathway to a low-carbon future is circular. Circular economy and the optimization of resources used in the energy system can be seen as a way to improve energy self-sufficiency." | Works in practice | "FIRO-O, OptiKom, Charity second-hand store “Spasibo”, Baltika Brewery (Carlsberg group) and St. Petersburg Urban Eco-Cluster are given as successful examples of circular economy principles in Russia and St. Petersburg." |

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| 11 | Environmental benefits of circular economy approach to use of cobalt | x | | | | "As shown in our results, cobalt recycling operations could have a significant contribution on reducing energy consumption, water use and mitigating GHG and SOx emissions comparing primary production." and "As cobalt is critical in developing and deploying green energy technologies, securing its sustainable and affordable supply - through recycling activities - could contribute to the SDG 7." | Potential | "This finding highlights the need for an appropriate strategy of secondary sources management that would ensure a better use of cobalt recycling in line with its circularity." |
| 29 | Environmental Sustainability and Supply Resilience of Cobalt | x | | | | "Cobalt (Co) is an essential metal for the development of energy-transition technologies, decarbonising transportation, achieving several sustainable development goals, and facilitating afuture net zero transition." and "However, a circular economy, keeping Co in the economic loop for as long as possible, is yet to be optimised at both regional and global scales." | Potential | Same quote |
| 16 | From Fossil Energy to Renewable Energy: Why is Circular Economy Needed in the Energy Transition? | x | | | | "However, their production, marketing, and above all, consumption are not entirely climate neutral, so society needs new practices, such as circular energy, to achieve a more efficient energy transition." | Potential | "The overall results back the idea of curtailing the existing levels of energy intensity and encouraging the exploration and the use of renewable energy sources as a policy tool against controlling the prevalent situation of carbon-based emissions in our subject group of countries." |
| 98 | From national champion to global player | x | | | | "In this respect, in 2015, Enel launched the Futur-e project, an internationally unique programme originally designed as a circular economy pathway to bring 23 Italian thermoelectric power plants, as well as the former Santa Barbara mining area, into eco-sustainable areas dedicated to science, art, culture, tourism or even new industrial activities, with the direct and active involvement of local communities." | Potential | Case study shows potential |

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| 37 | Data-driven Optimization of Biomass Retrofitting Pathway to Empower Circularity for the Oil and Gas Transition | x | | | | "The emerging trend of circular economy (CE) is a potential strategy to achieve the energy transition goal […]" | Works in practice | "This work serves as guidelines for the decision-makers and researchers to evaluate and strategize the circularity of the O&G industry by considering various biomass conversion pathways" |
| 34 | Economic Aspects for Recycling of Used Lithium-Ion Batteries from Electric Vehicles | x | | | | "With the growing number of EVs on the streets, it will be increasingly urgent to have recyclers in as many countries as possible. This can happen with the development of recycling facilities in different locations or with branches of prominent recyclers in places where this enterprise is lacking." | Potential with limitations | Found that recyling batteries is not easy and not lucrative |
| 120 | Energy efficiency services in buildings: A tool for energy transition | x | | | | "Consequently there are calls fbr a new sustainable business models. One group with particular attention are known as Product Services Systems (PSS). These PSS business strive to present value propositions that simultaneously meet economic, ecological and social needs economy. They have been recognized as a concept that can help from a classical linear economy (product) towards circular economy (service, function)." | Potential | "When the principles are applied in the context of energy use in buildings it is clear that EES and his variants offer opportunities." |
| 66 | Energy transition and the role of system integration of the energy, water and environmental systems | x | | | | "This work provides an overview of the impact of the energy transition on the environment, energy and water systems and the need for integration of these systems. Reduction of carbon-related emissions has been identified as the common topic through reliance on the circular economy concept." | Works in practice | Gives a overview of the status |
| 68 | Energy-based industrial symbiosis: a literature review for circular energy transition | x | | | | "This approach is claimed as effective aimed at reducing the use of traditional fuels in energy production, thus promoting a circular energy transition." | Potential with limitations | "From the literature survey conducted, it is concluded that energy-based IS is one of the pioneering fields to achieve energy transition from linear to circular economy. The field achieved an encouraging but not a sufficient number of success stories and barriers are still high and it starves for finding answers to a wide range of questions." |

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| 20 | Intelligent disassembly of electric-vehicle batteries: a forward-looking overview | x | | | | "Efficient recovery of these spent batteries is a significant way to achieve closed-loop lifecycle management and a green circular economy. It is crucial for carbon neutralisation, and for coping with the environmental and resource challenges associated with the energy transition." | Potential | "The review shows that AI could benefit the whole EV-LIB disassembly process to achieve a sustainable circular economy for the EV-LIB industry." |
| 2 | Minerals and energy interface in energy transition pathways: A systematic and comprehensive review | x | | | | "Circular economy approaches are useful and needed for smoother energy transition." | Potential | "This makes reuse and recycling of materials and circular economy approaches integral to minerals - energy interface." |
| 26 | Mining Residues Characterization and Sentinel-2A Mapping for the Valorization and Efficient Resource Use by Multidisciplinary Strategy | x | | | | "Currently, industry is largely dependent on imports and consumption of these materials, and in the future, following the global energy transition, this trend will drastically increase. For this reason, it is necessary to develop new strategies to meet the supply–demand of raw materials by strategic sectors and technologies. To this end, mining residues are turning into viable raw materials sources […]." | Potential | "These results represent the possibility of transforming an environmental problem (mining residues) into a resource potentially exploitable by industries knowing their composition and position in the study area." |
| 101 | Modelling strategy and net employment effects of renewable energy and energy efficiency: A meta-regression | x | | | | "First, the prioritization of regenerative resources should ensure that renewable and reusable resources are efficiently utilized as energy and materials." | Potential | Same quote |
| 132 | Paths to a low-carbon economy-The Masdar example | x | | | | "Masdar, […], is working on a broad slate of renewable energy and sustainability technologies in order to generate the skills, institutions and intellectual capital necessary for a low carbon future. Two: Masdar City, a carbon neutral, zero waste urban development and a world scale carbon capture and storage project, […]." | Potential | Article presents an optimistic outlook for the case study |

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| 70 | Progress towards a circular economy in materials to decarbonize electricity and mobility | x | | | | "The shift to renewable energy is one step towards building an economy on more circular material flows. Manufacturers of wind turbines, photovoltaics, batteries and vehicles—critical technologies to the clean energy transition—still primarily rely on feedstocks and inputs from natural resources as opposed to waste for processing and production" | Works in practice | "Extractive industries can ensure operations decrease energy and materials waste and repurpose old sites to offset environmental cost. Metal recycling can be improved through better scrap sorting, and process innovations for overcoming issues related to harmful residuals. Waste management industries must focus on increasing material recovery rates and energy efficiency through automation, artificial intelligence, educating producers, organizations, and consumers about impacts of decisions to pay, and equalizing and streamlining operations to demonstrate universality across the country." |
| 115 | PV waste management at the crossroads of circular economy and energy transition: The case of South Korea | x | | | | "An appropriate system for the monitoring, collection, and storage of PV waste needs to be arranged even before the volume becomes high enough for recycling to be economically viable. International cooperation could be a way to maintain the PV waste stream at an economically feasible scale. It would also be a good idea if the PV module could be designed in a way that would enable easier recycling or reuse." | Potential | Same quote |
| 116 | Renewable energy in the news: Environmental, economic, policy and technology discussion of biogas | x | | | | "Decentralised production and consumption of biogas is often argued to provide multiple opportunities for accelerating the transition towards sustainable development. This research focuses on the long-term coverage of biogas in two widely read Finnish newspapers." | Potential with limitations | "Second, the economic storyline has casted doubts on profitability of biogas production by emphasising the need for public subsidies. Newspaper coverage has focused on the micro level economic performance of energy producers and left the macro level economic implications of biogas with little attention. Third, the energy policy storyline has framed biogas predominantly as a local-level solution without extensively discussing a national level target setting for biogas." |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6 | Sequential optimization of process and supply chains considering re-refineries for oil and gas circularity | x | | | | "[...] green initiatives, which transition the conventional oil and gas sector towards a CE are necessary." | Works in practice | "The effectiveness of the proposed strategy is demonstrated through a case study in Malaysia." and "The analysis showed that the proposed strategy is capable of improving economic and environmental performances [...]." |
| 10 | Study of the energy recovery of slaughterhouse waste. The case of Tenerife | x | | | | "The energy recovery of this waste through anaerobic digestion to produce biogas would enhance the use of renewable energies, contributing to the meat industry's energy independence and better management of the waste generated by this industry in Tenerife, promoting an energy transition towards cleaner energies." | Potential | "The animal by-products have a potential for energy recovery through anaerobic digestion." |
| 58 | Sustainable energy transitions require enhanced resource governance | x | | | | "Our findings underscore the importance of institutional instruments that enhance the resource governance of entire low-carbon technology supply chains, along with circular economy practices" | Potential with limitations | "In this regard, another important perspective obtained from our analysis is that a suite of circular economy strategies alone will not entirely offset the concomitant increase in resource extraction in countries with weak, poor, and failing resource governance.” |
| 22 | Techno-economic feasibility and environmental sustainability of waste-to-energy in a circular economy: Sri Lanka case study | x | | | | "The study presented in the paper has examined WtE in a circular economy as a solution that can have economic, financial, social, and environmental co-benefits through efficient use of natural resources, reduced emissions, and fostering innovation." | Works in practice | "This pioneering case study can be used as a basis for immediate action to solve waste management issues within a circular eonomy helping similar economies in the Asia Pacific region in their efforts to achieve net zero emission targets by the middle of the century." |
| 94 | The Material Basis of Energy Transitions | x | | | | "As a concept, the circular economy is also well suited to dealing with issues of materials supply risks, which are particularly pertinent to the rapid adoption of renewable energy technologies as outlined in this chapter." | Potential | "However, recycling alone may not be enough to avoid potential resource limitations. A combination of storage technologies (as well as other flexible options for grid applications) could, therefore, be beneficial, as could the use of emerging energy storage technologies based on more abundant materials like magnesium or sodium." and previous quotes |
| 93 | The role of a circular economy for energy transition | x | | | | "Das Konzept der Kreislaufwirtschaft eignet sich auch gut für die Bewältigung von Risiken bei der Materialversorgung, die bei der raschen Einführung von Technologien für erneuerbare Energien, ..." | Works in practice | Same quote |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 4 | The value of recycling for low-carbon energy systems - A case study of Germany's energy transition | x | | | | "[...] without recycling in today's energy system, additional costs of 13 billion €/a would arise." | Potential | "Recycling is a cost—effective measure in the context of GHG reduction strategies" |
| 88 | Thermodynamic rarity and recyclability of raw materials in the energy transition: The need for an in-spiral economy | x | | | | "This is because clean technologies require huge amounts of many different raw materials. The rapid exhaustion of mines necessitates an increase in recycling and reuse, that is, a “circular economy”." | Potential with limitations | "We aim to strive toward an advanced economy focused on separating techniques and promoting circularity audits, an economy that inspires new solutions: an in-spiral economy." |
| 28 | Toward carbon neutrality: Uncovering constraints on critical minerals in the Chinese power system | x | | | | "In order to solve such a problem, it is critical to seek alternative minerals, such as secondary resource from urban mining through the implementation of circular economy." | Potential | "Finally, several policy recommendations are proposed to help improve the overall resource efficiency, such as strategic reserves, material substitutions, and circular economy." |
| 35 | Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system | x | | | | "[...] addressed this gap, the potential circularity of the electricity system, by analyzing the stocks and flows in that system towards 2050, including electricity generation, storage and transmission technologies, for both bulk metals and critical minor metal." | Potential | "The metal demand is substantially larger in scenarios with a higher level of self-sufficiency in (renewable) electricity generation, thereby showing a potential trade-off between climate and circularity related policy goals." and "Circularity can be further enhanced when collection and recovery rates improve." |
| 1 | Towards a more resource-efficient solar future in the EU: An actor-centered approach | x | | | | "This paper provided an overview of the required transition towards more resource-efficiency in solar PV, and showed how the actors involved navigate this transition within the existing policy landscape." | Potential | "Altogether, resource-efficiency is not sufficiently supported, while it is considered extremely important in the future of solar PV [...]." |
| 47 | Towards Circular Port–City Territories: Rotterdam and the Port Back to the City | x | | | | "Important topics like climate change and energy transition are putting pressure on the port authority to find solutions to remain competitive in the future, not at the expense of the environment." | Potential | "New approaches and solutions that look at integration and circularity rather than separation are necessary." |
| 113 | Waste feedstocks for sustainable chemicals and fuels | x | | | | "In this scenario, the circular economy model promoting the reuse of material instead of the disposal would allow for a better use of resources and energy." | Works in practice | "The synergy between two different industries, waste management and the chemical industry, may account for a strategic solution in line with the principles of a circular economy and is sustainable from technical and economical points of view, as shown by two case studies here analyzed." |

**Appendix H: SLR sub RQ2 table showing categorization of included articles according to their respective sub-topics.**

| Author | Critical Finite Resources | Solar Energy | Wind Energy | Biogas | Batteries, Energy Storage and Mobility | Artificial Intelligence and Data Management | Policy |
|---|---|---|---|---|---|---|---|
| Abdelshafy & Walther, 2022 | X | | | | | | |
| Abdul Manaf et al., 2021 | | | | | | X | |
| Arias et al., 2022a | | | | | | X | |
| Barragán-Escandón et al., 2017 | | | | | | X | |
| Bleicher & Pehlken, n.d | | X | X | | | | X |
| Bonfante et al., 2021 | | | | | X | | |
| Busch et al., 2017 | | | | | X | | |
| D. Dong et al., 2022 | X | | | | | | |
| de Martino, 2022 | | | | | | | X |
| Duran et al., 2021 | | X | | | | | |
| Earl et al., 2022 | X | | | | | | |
| Fytili & Zabaniotou, 2022 | | | | X | | | |
| Gimeno et al., 2020 | X | | | | | | |
| Guglietta et al., 2022 | X | | | | | | |
| Haas et al., 2015 | X | | | | | | |
| Ishaq et al., 2022 | | | | | | | X |
| Kalchenko et al., 2019 | | | | | | | X |
| Khan et al., 2022 | | | | | | X | |
| Kim & Park, 2018 | | X | | | | | |
| Koese et al., 2022 | X | | | | | | |
| Koytsoumpa et al., 2021 | | | | X | | | |
| Liaros, 2022 | | | | | | X | |
| Lima et al., 2022 | | | | | X | | |
| Llera-Sastres et al., 2020 | | | | | | | X |
| Lyytimäki, 2018 | | | | X | | | |
| Meng et al., 2022 | | | | | | X | |
| Mirletz et al., 2022 | | X | | | | | |
| Mishra et al., 2022 | | | | | | | X |
| Montakhabi et al., 2021 | | | | | | X | |
| Mulvaney et al., 2021a | | X | X | | X | | |
| Nechifor et al., 2020 | X | | | | | | |
| Niang et al., 2022 | | | | X | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Okafor et al., 2021 | | | | | | | X |
| Pulselli et al., 2021 | | | | | | X | |
| Rachidi et al., 2021 | X | | | | | | |
| Rahimpour Golroudbary et al., 2022 | X | | | | | | |
| Razzaghi Asl, 2022 | | X | | | | | |
| Salladini et al., 2019 | | | | X | | | |
| Samarasinghe & Wijayatunga, 2022 | | | | X | | | |
| Samoylov, 2019a | X | | | | X | | |
| Sankaran, 2019 | | | | | | X | |
| Scarpellini et al., 2021 | | | | | | | X |
| Schwartzman & Schwartzman, n.d. | | | | X | | | |
| Srivastava & Kumar, 2022 | X | | | | X | | X |
| Stavropoulos & Burger, 2020 | | | | X | | | |
| Su & Urban, 202 | X | | | | | | |
| Sun, 2022 | X | | | | | | |
| Tabelin et al., 2021 | | | | | X | | |
| Valero & Valero, 2020 | X | | | | | | |
| van der Voet et al., 2019 | X | | | | | | |
| van Oorschot et al., 2022 | X | | | | | | |
| Velenturf et al., 2021 | | X | X | | | | |
| Watari et al., 2021 | | | | | | | X |
| Wei et al., 2022 | X | | | | | | |

## Appendix K: Circularity of the German Battery Industry – A Case Study of Circu Li-ion

### Appendix K.I: Transcript of Expert Interview 1 (Original translated from German into English)

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**Interviewer:** **Matty Friedl (**hereinafter **MF**)

**Interviewee:** **Cecilia Wiesböck (**hereinafter **CW)**

**Date:** 10-11-2022

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**MF:** Quickly introduce yourself and your position within Circu Li-ion.

**CW:** I am Cecilia, Head of Partnership at Circu Li-ion. Circu Li-ion is a startup founded in October 2021 in Luxembourg and has developed a proprietary battery cell upcycling process that is able to recover up to 80% of end-of-life battery cells and components. I take care of three main topics: First is customer success, where we follow a truly customer centric approach and identify our customer segments and adapt our product portfolio accordingly. Second, I take care of branding and marketing. Here, we just launched a new brand personality that actually fits to the brand we want to perceived as: A bold, new, revolutionary and innovative player that can hold the promise of accelerating the green revolution. Thirdly, I take care of HR and employer branding and making sure that Circu Li-ion is an attractive company to work for and that we attract the outside talent that we need to move the needle and, again, accelerate the green revolution.

**MF:** Please describe the problem that Circu Li-ion solves and its solution.

**CW:** Increasing electrification of our economy results in an exponential growth of lithium battery demand. This excess demand of lithium is currently tackled with recycling. Traditional recycling processes destroy 100% of the battery, although only 10 % of battery cells reached their end of life. Our solution is an automated upcycling process, which is able to automatically disassemble and diagnose each battery pack down to the cell level. Battery cells with a high state of health are a true resource that can be used for second life solutions. Our process recovers substantially more resources, saves costs and $CO_2$.

**MF:** Please describe competitors and Circu Li-ion's USP.

**CW:** While there are some new players emerging in the space of lithium battery upcycling. Circu Li-ion is the only one with a truly automatic technology going down to the cell level while building the largest used cell database.

**MF:** How do you analyze the market size? How big do you think the business case can become?

**CW:** We are targeting a huge total addressable market of 100b USD of global lithium-ion cell value. Looking more granular, the value of reused cells is 5b USD and can be defined as serviceable available market. The market we defined as serviceable obtainable market we plan to capture is 500m USD. It is important to mention that ultimate vision is the upcycling of everything. So, achieving a mindset shift from new to reusing. Secondly, the vision is also targeted towards data collection. Circu Li-ion is planning to build the biggest battery data library that exists and host all battery data there in order to understand various battery types perform and what their state of health is, how many cycles they have. That would also have big implications on the design of new batteries in the future.

**MF:** Who are your customers? Why did you choose micro- mobility providers as go-to-market strategy?

**CW:** Our customers can be differentiated into the following segments: Micro- mobility providers, hardware producing companies and industry players, recyclers and energy storage solution companies for cells. We chose micro mobility provider as the market is ready if compared to for example OEMs. Micro mobility providers have access to EoL batteries as they have pushed into the electric market the soonest, therefore their batteries are end of life the soonest. So, the main point really is market readiness. Furthermore, they have a strong emphasis on sustainability as their USP and storyline, which is why they are always looking to make their business more sustainable.

**MF:** Please describe the business model.

**CW:** The business model divided into two pillars. The first one is machine- as-a-service. Here you have a subscription/ renting model of the machine with certain software upgrades that is needed to perform to always extend the battery library. You have certain amounts of batteries that are already part of your library and if new batteries need to be added, a software update needs to be performed. So, the base is the hardware, but the scalability comes through the software. As a second pillar we have "service only", which is currently offered to clients without a lot of EoL batteries and more targeted towards pilot projects. In our facility in Karlsruhe we actually treat the batteries for them and send their second life cells (for example integrated into products like ESS) back to them. But this is not a long-term solution as we want to keep logistics at a minimum to avoid $CO_2$ emissions. In short, if there are big quantities: Machine as a service makes the most sense and if there are smaller quantities, service only is the way to go. Eventually, every case should develop into a machine as a service model.

**MF:** What is your pricing strategy?

**CW:** The pricing strategy consists of different building blocks. Firstly, there is always a fee for set-up as the entire production line has to be set up and reserved for the specific service. This applies only one time. The second part is dismantling and diagnostics on a battery pack level or kg level. Thirdly, data reports and fourthly logistics are priced separately. Lastly, also the batching and sorting is a separate cost block. The biggest cost block is always the data part as this the most valuable part being the fundament for many business and technical related questions. All of these components are priced depending on the specific case and customer.

**MF:** How would you describe your team?

**CW:** The team is mainly build out of engineers as the key component lies in dismantling and diagnostics, which is a core engineering challenge building an automated upcycling process around it. Those engineers come from various backgrounds including PhD holders from the best engineering universities in Europe always developing the product further. The business team currently consists of four people, who are leading the execution and scale up part of the solution across Europe with the clear goal to always align product offering to customer needs while keeping the strategic focus. Overall, the team is really mission driven to foster the green revolution.

**MF:** How do you see the regulatory and financial environment in regard to governmental laws and funding options?

**CW:** Generally speaking, the overall regulatory and financial environment is good for Circu Li-ion as Climate Tech and specifically topics regarding the sustainability of batteries are "hot topics". There are many grants on EU level for companies from those segments. Furthermore, politics have gotten under pressure in order to make the electrification of the economy more sustainable.  Regulations like Supply chain transparency law, European battery law, Recycling quotas, CSRD and the EU's plan to end sales of new $CO_2$ emitting cars by 2035 are in favor of Circu Li-ion's business plan. Furthermore, the current energy crisis has shown how important it is for countries and businesses to electrify and move aways for dependencies and fossil fuels.

**MF:** Where do you see risks/ How could the business fail?

**CW:** Generally speaking, I don't see real risks of the business failing. Nevertheless, as for every startup, it is important to not lose focus on customers and product development within the key customers. As the topic is so interesting for many different parties, the company must keep their strategic focus instead of trying to serve too many different use cases.  Externally, unfortunately as long as they are not forced by regulations, too many companies are hesitant when it comes to investing into sustainability. Especially in the current macroeconomic environment customers are reluctant.

**MF:** What would you wish from the government (German, Luxembourg or on EU level) to support deep tech and innovative startups?

**CW:** I would wish for processes in regard to financial support from the EU to be smoother and less bureaucratic. Furthermore, it would be important for startups that have been approved for grants to first receive the financial support and then be able to spend it. Right now, it is often the case that startups have to first spend the money and can reclaim it later. This brings many startups in a difficult situation as cash flow is extremely important and hard to remain positive. Further, the way of getting the money back is very bureaucratic and requires high amounts of capacities. Furthermore, some grants or programs prohibit startups to apply for others, which makes the selection hard and increases the possibility of not receiving support at all. Even though, there are programs such as ScaleUp Landing Pad Hamburg, which we participate in, I would wish for even more private and public support when it comes to building startup ecosystems.

**MF:** Thank you so much for your time!

## Appendix K.I: Transcript of Expert Interview 2

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**Interviewer:** **Matty Friedl (**hereinafter **MF**)

**Interviewee:** **Dr. Xavier Kohll (**hereinafter **XK)**

**Date:** 26-11-2022

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**MF:** Hi Xavier, thank you so much for joining and for your time. Could you quickly introduce yourself and your position within Circu Li-ion?

**XK:** I am Dr. Xavier Kohll, CTO and Co-founder of Circu Li-ion. We are startup company with 20 employees working on automated upcycling of lithium-ion batteries.

**MF:** Having already touched a little upon what Circu Li-ion does, could you dig deeper into the problem you saw in the market and how Circu Li-ion solves this problem?

**XK:** So the biggest problem we're facing right now is that we need to have an economy running on renewable energies. And there are multiple technologies contributing to that. One of the largest contributor is lithium- ion batteries. Those can be powered by green energy and they can store their energy making the energy available for usage whenever it is needed. Most lithium-ion batteries are currently used in micro mobility and in the EV space. The problem is that we currently do not have enough production capacity for the high amounts of batteries needed in all those new vehicles. Therefore, the lithium- ion batteries we have must be used as efficiently and as long as possible. Now, what happens to those batteries when they reach their first end-of-life in for example e-scooters? When they reach 80% remaining capacity (state of health), they are not good enough anymore for their primary use, which is why they are recycled. But the stages of repairing and reusing are skipped in that process. That is why, we have created an automated battery disassembly and diagnostic process to recover the battery cells that still work and give them a second life. Why is that so important? When batteries reach for example 70% state of health, they can still be used for a long time approximately until 50% capacity. At this stage, it is important to mention that a battery pack consists of multiple battery cells depending on the respective model, which can all have different SoHs. Therefore, battery pack SoH is an average of all battery cells combined. Traditional recycling destroys a lot of value not making use of the capacities until 50%.

**MF:** You mentioned that traditional recycling destroys a lot of value, could you describe current recycling processes more in detail?

**XK:** On a global scale, you have three different recycling processes. The first one is pyrometallurgical, which is the current status quo in most regions. Then you have the hydrometallurgical process, which exists in several parts of the world, but is not widely adopted. Lastly, there is direct recycling, which is still in research and development and not in practice yet. If we now focus on Europe, as far as I know there is no hydrometallurgical plant in Europe that works at scale. So, what is the difference between the hydrometallurgical and pyrometallurgical process? In a pyrometallurgical process, temperatures of over 1.500 °C are used and not all raw materials can be recovered. Especially, all lithium is lost and all plastic is burned in a pyrometallurgical process. A hydrometallurgical process solves some of these problems and some of lithium and other raw materials can be recovered.

When nowadays a lithium ion battery reaches end-of-life in Europe, the standard way is to burn it first to remove all plastics and organic materials. Then, the battery is crushed in a shredder and is subsequently burnt again. Recyclers care most about the nickel and mangan that they recover from the resulting black mass as it has the most value for them right now. So, currently recycling inefficiently recovers lithium and focuses too much on nickel and mangan while neglecting lithium. Nevertheless, they are increasingly facing a problem as the new battery directives from the EU force them to increase recycling efficiencies also on lithium.

**MF:** Please describe your technological innovation.

**XK:** Let's take a concrete example to illustrate the process. A micro mobility provider has 50.000 e-bikes. Currently, the micro mobility provider has the problem that their batteries in the scooters last for roughly two years. Afterwards, they are sent to recyclers, where they are burned as described previously.

We as Circu Li-ion sit in between the micro mobility company and the recycler. We automatically diagnose every battery pack to understand which battery packs have enough state of health that makes sense to reuse them. Afterwards the battery packs with enough SoH go through an automated disassembly line, where attery packs are automatically opened using robotics and computer vision. The battery cells are disassembled and extracted from the opened battery pack. We recover all of the lithium ion cells that make up a battery pack. Thus, we capture the value of lithium-ion cells and give them a second life. Battery packs with very low states of health are dismantled to a certain extent, which is a more destructive way of disassembling, and afterwards send to recyclers. That way, recycling efficiency is improved. Also, we are gathering all data on the diagnosed battery cells to create the largest battery library.

Our approach can give >80% of otherwise recycled cells a second life, this reduces operating cost by >30%, whilst doubling the battery lifetime and reduce $CO_2$ emissions by 80%.

**MF:** Could you talk about the vision of Circu Li-ion?

**XK:** The vision of Circu Li-ion is to not only process battery packs from micro mobility providers and power tools, but also from EVs. Here the process will be exactly the same.

**MF:** What would you wish for from the government to accelerate startups like Circu Li-ion?

**XK:** So for startups, the two most important things until they are cash flow positive, are: product and financing. Europe is already offering some support when it comes to financing, which is important as the more financing the easier it is for startups. Apart from financing, I would value it as important to create even more startup ecosystems, where we assemble a lot of talented young people to solve the biggest challenges we are facing. Young and talented people should be motivated to change the status quo and feel empowered to create technology in an ecosystem of change.

**MF:** Where do you see risks or obstacles in scaling the company?

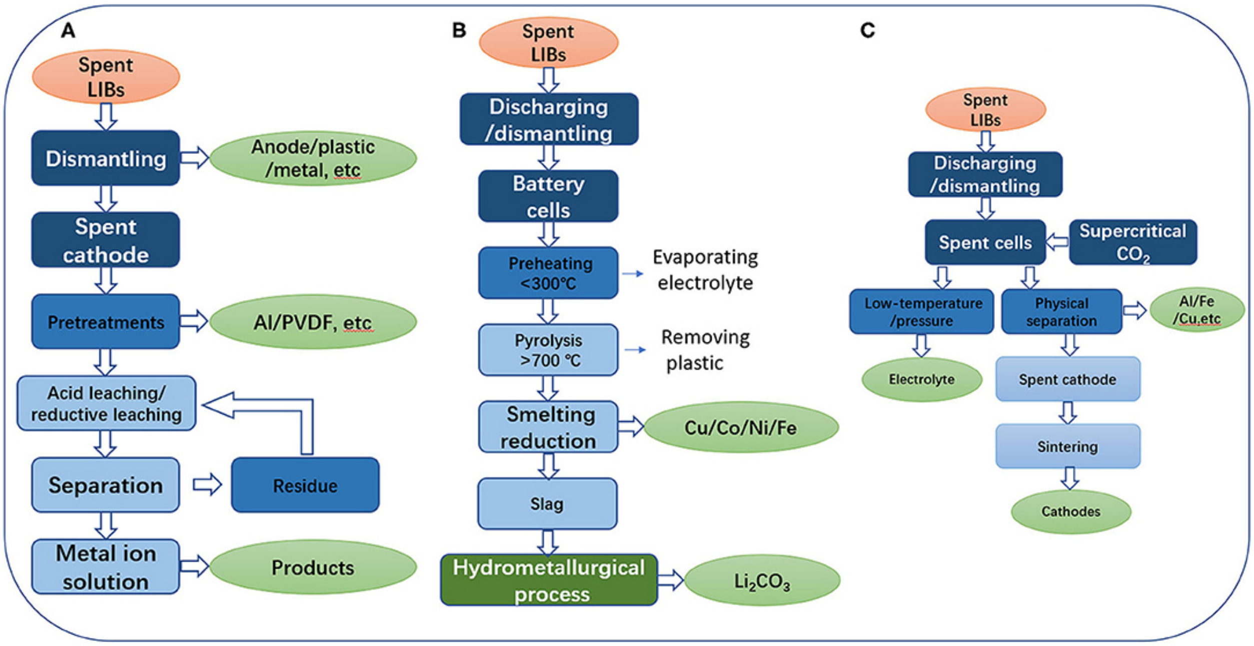
**XK:** For every company there are internal and external risks. Internal risks can be from my point of view categorized into three sub areas: human factor, technological factor and funding factor. Every startup needs to have the best possible employees, who want to change something. Furthermore, they have to have the right amount of funding and they need to minimize technological risks as much as possible. Externally, the startups need to be in an environment, where they can hire the respective hard working people.

Furthermore, building the first automatic disassembly line is naturally hard, but I think it is manageable. Going into serial production is even more challenging. If one problem occurs in the pilot disassembly line that is not noticed and solved in the beginning, it gets extremely costly and hard to solve when scaled up and ten machines are produced based on the pilot case.

Building an MVP or prototype is done quickly but replicating that prototype for mass production is the hard part startups face. Especially for hardware connected startups like we are.

**MF:** Thanks so much for your insights, Xavier!

## Appendix K.II: Current recycling processes of LIBs



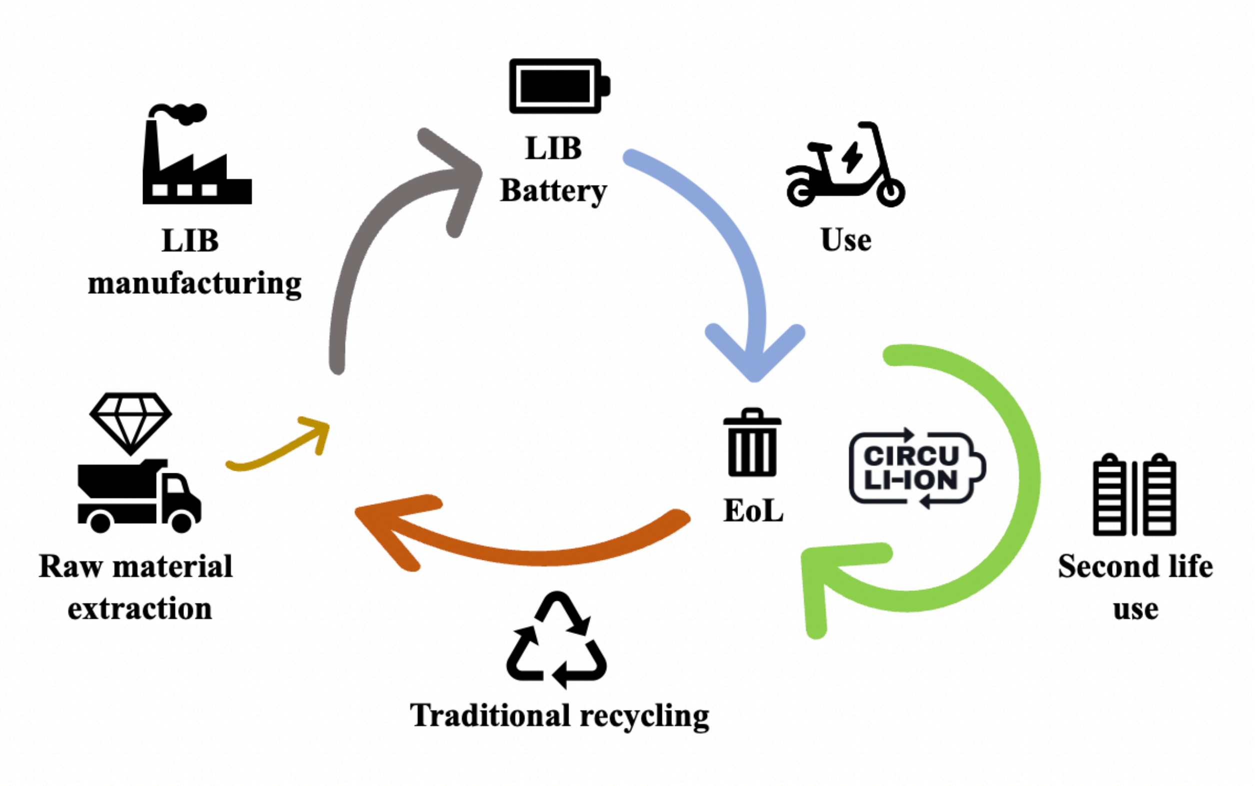
A: Hydrometallurgical process

B: Pyrometallurgical process

C: Direct recycling process

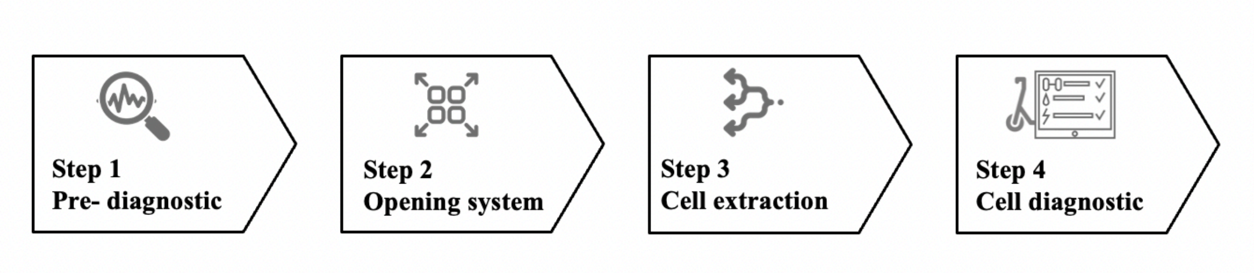
Source: (Zhou et al., 2020)

### Appendix K.III: LIB lifecycle prolongation with Circu Li-ion's involvement



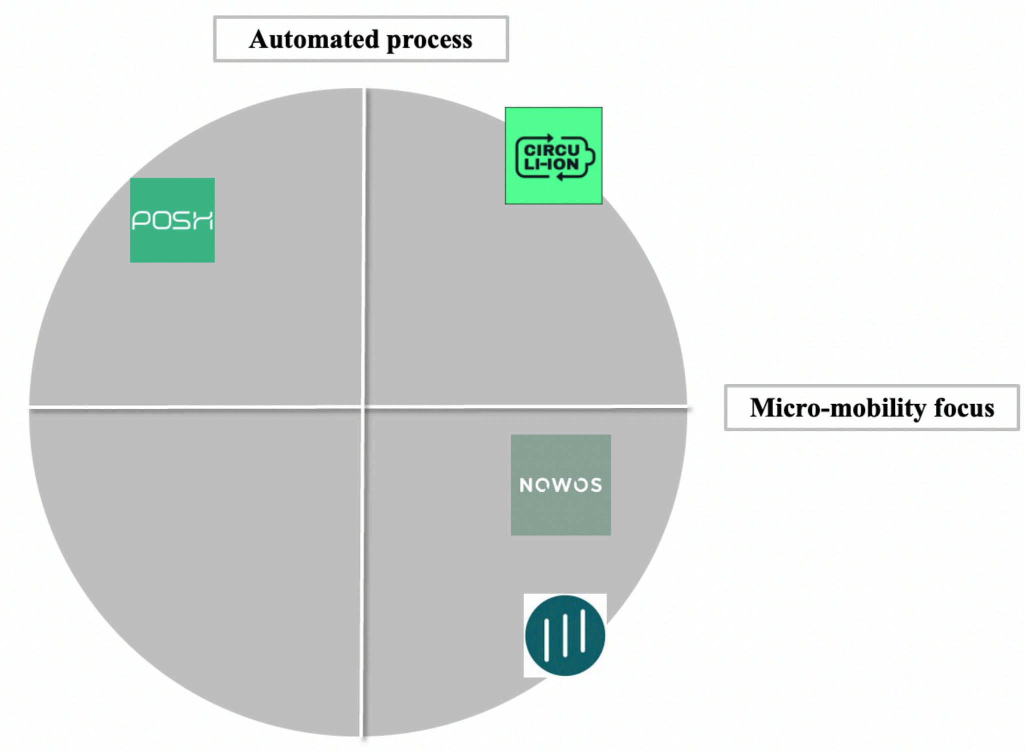
Own illustration

### Appendix K.IV: Circu Li-ion automated upcycling process

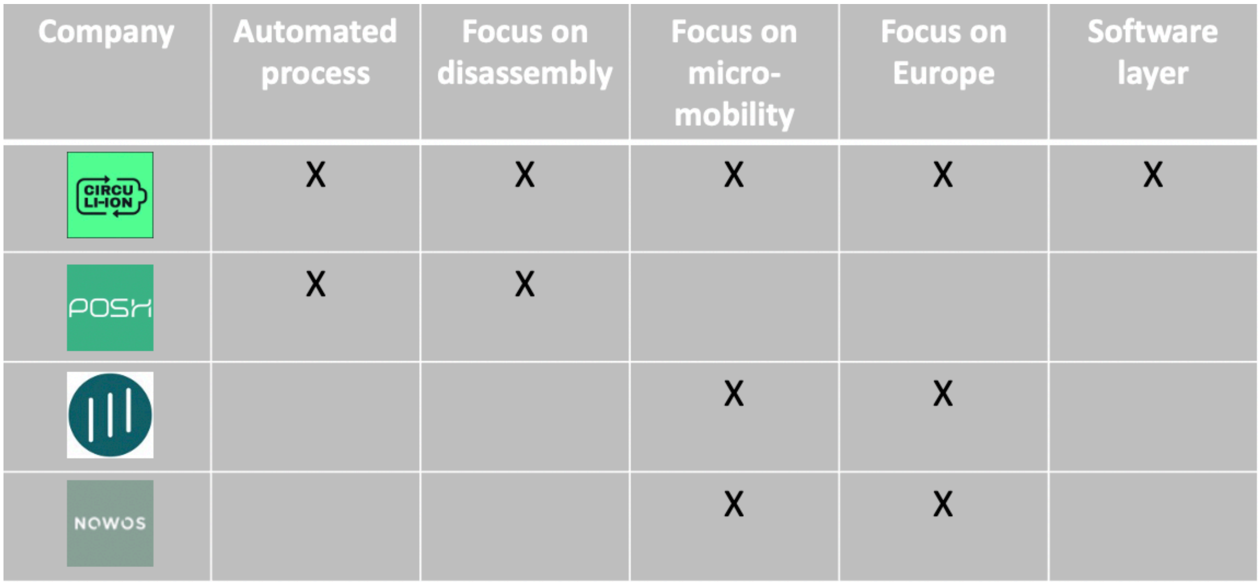


Own illustration

## Appendix K.V: Competitor Matrices



Own illustration



| Company | Automated process | Focus on disassembly | Focus on micro-mobility | Focus on Europe | Software layer |
|---|---|---|---|---|---|
| CIRCU LI-ION | X | X | X | X | X |
| POSH | X | X | | | |
| | | | X | X | |
| NOWOS | | | X | X | |

Own illustration