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Adopting a sustainable energy system through the implementation of a circular economy in the german energy transition

CIRCULAR ECONOMY IN THE GERMAN ENERGY TRANSITION: THE SOLAR INDUSTRY – CASE STUDIES ALONG A PHOTOVOLTAIC SYSTEM'S LIFECYCLE STAGES

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Abstract

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 along a Photovolatic systems life cycle with the objective to understand how current stakeholders implement and contribute to CE, how they capture value from it, and to identify the limitations that arise in this process.

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
EE	Energy Efficiency
EoL	End-of-Life
EV	Electric Vehicle
GHG	Greenhouse Gas
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

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. Due to university regulations, this version of the study only includes market research on solar energy.

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. Circularity in the German Solar Energy Industry – Case Studies along a PV’s Lifecycle Stages

5.1 Circularity in the German Solar Energy Industry – Case Studies along a PV's Lifecycle Stages

I. Introduction

Solar energy presents a great possibility to mitigate climate warming. Solar energy has a positive environmental footprint, is the cheapest source of energy, and offers excellent scale-up potential. The focus of this industry is to scale manufacturing, increase the number of installed Photovoltaic (PV) systems, and to further reduce prices. However, "with great power comes great responsibility" (Lee, 1962). In an industry already striving for a sustainable transition, the goal should be to minimize the negative impact on the environment truly. The solar industry will significantly produce electronic waste in the coming years. While experts predict Germany's readiness regarding waste collection processes, the proper waste management of the discarded PV modules is questioned (El-Khawad et al., 2022). The manufacturing of PV systems is highly dependent on critical resources and supply chains in China, possibly leading to rising prices and compromising the competitiveness of solar energy compared to other REs.

This study argues that the urgency of transitioning to RE in the short term should not jeopardize long-term environmental impacts. The implementation of CE practices presents the possibility of mitigating these challenges. However, the complexity of this undertaking is becoming present considering the advanced ET, its planned expansion volume, constantly emerging innovations (i.e., flexible PV modules, modules producing energy also from indirect light, multiple solar cells) and the need to pursue and implement these innovations simultaneously (Öko-Institut e.V., 2022; Project Drawdown, 2022). The objective of this section of the study is to understand how current stakeholders implement and contribute to CE, how they capture value from it, and to identify the limitations that arise in this process. Over the lifetime of a PV plant, many stakeholders get involved that are essential to close the loop. Therefore, a cross-case analysis is conducted on three case companies supporting CE along a PV's lifecycle to analyze CE practices, stakeholder participation, and cooperation.

II. Methodology

To create a comprehensive understanding of the current situation of the circularity of PV systems in Germany it is essential to conduct an in-depth analysis of the existing literature. Additionally, this study employs an exploratory case study approach. Different applications of CE during the lifetime of a PV plant are analyzed to investigate the current implementation in practice and to draw conclusions about the future development of the phenomenon under study (Yin, 2009). The case company selection process targeted companies that are frontrunners in their field, highly innovative and competitive. Due to the rapid innovation dynamics in this context and to ensure the validity and accuracy of the literature only highly recent publications from the search engine Scopus, reports from research institutes (e.g., Fraunhofer Institute, IRENA), political associations (e.g., BMWK, Bund für Solarwirtschaft, Umweltbundesamt) and industry experts that play significant roles in the topic area are considered. Also, research in the form of publicly available data and a primary research component through semi-structured interviews are conducted. Each case is examined separately in depth to understand its contribution to CE and its limitations. Afterward, all cases will be analyzed in a cross-case analysis to create comparability and identify necessary cooperation opportunities (Ramanathan et al., 2017; Stake, 2008). Furthermore, this procedure should allow the identification of general trends and serve for verification (Yin, 2009).

III. The German Solar Energy Sector

To mitigate the effects of climate change Germany has decided to make a fundamental transition towards renewable energies (REs). Currently, the share of REs in Germany's primary energy consumption accounts for 16.1%. Solar energy generates 1.7% of the energy produced, making it the most producing RE source behind wind (Destatis, 2022b). The German Federal Ministry for

Economic Affairs and Climate Action aims to cover 30% of the primary energy consumption and 65% of the gross electricity consumption by REs until 2030 (UBA, 2022a). Solar power is to cover approx. 25% by 2030 and approx. 31% by 2040 (BMWK, 2022). Currently, 2.2 million PV panels are installed in Germany with a power generation of 59 GW. To meet set goals, 5 to 10 GW of solar power should be added annually (not including replacing obsolete systems) (Fraunhofer Institute, 2022).

While it is agreed that until significant power-to-power storage capacity or storage hydroelectric plants are accessible on the grid, it is not possible to rely solely on RE, the capacity of increase is far from exhausted. The expansion of solar energy does not conflict with the space required, for example, for nature conservation or agriculture (Wirth, 2022, Appendix J.I). In Germany, roofs alone offer a technical potential of 1000 GW which is over four times more than the GW totally required by 2040. Current use only claims 10% of the potential of the roofs and 1% of the facades (EUPD Research, 2022; Wirth, 2022). Moreover, recent life cycle assessments of PV systems show that they perform well in terms of their energy payback time (EERE, 2022). On average, the energy amortization period of a PV system installed in Europe is between 1.05 to 1.18 years, while the expected lifetime is 20 to 30 years (Fraunhofer Institute, 2022). Even so, the efficiency level, the ratio of emitted electrical energy to incident solar energy, for conventional models lies only at around 20% (Kamaraki et al., 2021; Photovoltaik.org, 2022). Nevertheless, various innovations (e.g., multi-junction solar cells, use of lenses) can increase a solar cell's efficiency beyond this (Freist, 2019; Marsh, 2019). In addition, the high acceptance of solar energy among the population, also compared to other RE sources, contributes to the potential of solar energy (AEE, 2021; Statista, 2021). This popularity is supported by the continuously decreasing solar power generation prices and is further favored by various government incentives (IRENA, 2021; Wirth, 2022). In the last year in Germany, feed-in tariffs have been increased, credit terms have improved, tax breaks and subsidies are available nationwide, and additional subsidies are available depending on the state (Wirth, 2022).

IV. The Need for a Circular Solar Energy

With the expansion of REs, conflicts and tensions arise. Renewable technologies are under pressure to be scaled up as quickly as possible to decarbonize the economy and limit the effects of climate change. At the same time, the minimization of cumulative waste during the life cycle and environmental impacts are vital aspects to consider, making the scale-up more complex and prolonged (Ovaitt et al., 2022).

The preceding systematic literature review states that PV panels will be one of the most significant contributors to electronic waste in the future (Mulvaney et al., 2021). The IRENA (n.d.) estimates a PV material waste volume of 60 to 78 million tons worldwide by 2050. In Germany alone, the cumulative waste will add up to 4.3 million tons (Wehrmann, 2021). It can be assumed that the waste quantities will be even higher since waste at the PV production level or waste created for economic reasons through early decommissioning for repowering or insurance claims are not being considered (Tsanakas et al., 2020). Between 2025 and 2030, the PV power supply system will be put to the test for the first time, as 90% of the PV systems have been installed in the last 20 years and are expected to have an average lifetime of 20 to 30 years (Enerix, n.d.; SolarUnited, 2022.; Statista, 2022b). Moreover, the waste management infrastructure is in question regarding the collection, storage opportunities and proper waste processing (Kim & Park, 2018; Mirletz et al., 2022; El-Khawad et al., 2022; Franco & Groesser, 2021).

Additionally, PV module production relies on raw materials. The need for raw materials, especially CRMs (silicon metal, gallium, germanium, and indium), is expected to rise significantly as PV panel production increases (Guzik et al., 2022; SolarUnited, 2022). The further exploitation of these materials will lead to rising prices endangering the industry's traction due to high input costs leading to little cost efficiency. While most of the materials used in a PV system are not scarce, their extraction still is very energy-intensive and expensive (Hengstler et al., 2021). The value of recyclable PV raw materials today is about $170 million annually. Experts estimate that this value is set to reach $2.7 billion in 2030, rising to $80 billion a year by 2050 (Rystad Energy, 2022).

V. Case Study Analysis: Circularity along a PV's Life Cycle Stages

This study will analyze the circularity of PV systems along their entire life cycle through a cross-case analysis of three different case companies, along the design and manufacturing stage, the use, and the end-of-life (EoL) stage (IEA, 2019). A PV system passes through these different stages in a period of about 30 years. While the stages vary considerably in their duration, each stage needs to contribute to closing the loop, as the different stages are highly dependent on each other. Implementing a CE principal at one stage can lead to issues at other stages. Therefore, this whole-system view is particularly appropriate because it considers interdependencies and identifies enabling connections to get to a CE (Asante et al., 2022).

When retiring from operation, a PV module enters the EoL stage. Due to the topicality of the expected waste problem, this study takes the EoL stage as the starting point. Besides exceeding its lifespan, weather damage and installation errors, as well as consumers upgrading the system early to take advantage of technological improvements are reasons for a PV plant to enter this stage (EERE, 2022). Most studies on the implementation of CE in the solar industry focus on the EoL stage, which shows the relevance of this stage and the desired expectation for innovations to come (cf. El-Khawad et al., 2022; Hagelüken & Goldmann, 2022; Heath et al., 2020; Nevala et al., 2019). The R principals coming to use in this stage – Recycle (R8), Recover (R9) and partly Repurpose (R7) – are the ones furthest from a truly circular system as waste is already being created and then managed (Potting et al., 2017). The use stage of a PV panel starts with the installation of the panel (on roofs, facades, in parks, etc) and ends with the disassembly of the system right before entering the EoL stage. To implement circularity, the R strategies Reuse (R3), Repair (R4), Refurbish (R5), and Remanufacture (R6) are most relevant. This stage aims to prolong the life of the product. The fabricant stage of a PV plant covers the material production (solar silicon, metal pastes, connector wires, plastic films, solar glass, glass coating), the production of intermediate and end products (modules, cables, inverters, mounting racks, tracking systems) as well as the mechanical engineering for cell and module production racks, tracking systems) as well as the mechanical engineering for cell and module production (Wirth, 2022). In the fabrication process, equipment should be produced that increases the chances of circularity of a PV system after sale, especially considering CE principle two and applying R2 (Reduce). The emphasis on the design stage lies with developing processes and products, keeping their eventual circulation in mind. This stage influences all the following ones. Design can be the point where it is decided whether a product can be circulated or not (Ellen MacArthur, 2022b). All Rs should be considered during this stage.

V.1 Solarmaterials – Returning Materials to the Cycle at the EoL Stage

Solarmaterials is a start-up founded in 2021 that deals with the recycling of PV modules. By using physical-mechanical processes, they eliminate the use of costly and less sustainable chemicals. Their goal is the complete recovery of all raw materials. Their technology can increase the value of captured materials compared to industry standards. They are currently running a campaign recycling 1000 PVs, planning to open two fully automated recycling plants and reach break-even in 2024 (Solarmaterials, 2022a).

V.1.1 How do they support CE?

Solarmaterials is eliminating waste and pollution in accordance with the first CE principle. Through recycling activities, Solarmaterials feeds previously wasted materials back into the system. In addition, the recovered materials minimize pollution as they have an 80% lower energy consumption than newly mined ones (Solarmaterials, 2022a).

The WEEE, the legislation for Waste from Electrical and Electronic Equipment, stipulates that 80% of the PV system should be recycled (WEEE, 2012). This percentage is already covered by glass alone, which is easy to recycle but is neither valuable nor scarce. More problematic is the reuse of the materials in the solar cell, which make up about one percent of the mass. These include valuable silicon and metals such as copper, silver, zinc, cadmium, and lead (El-Khawad et al., 2022). Separation is costly because they are welded together in plastic foils. Therefore, incineration is often the only economical option currently, making it only possible to recover 40% of the raw material value (Solarmaterials, 2022b). However, through their physical-mechanical process, Solarmaterials is making it possible to recover those precious materials (Solarmaterials, 2022a).

V.1.2 How do they benefit from a CE?

Solarmaterials' business model is an excellent example of how CE creates new business and job opportunities (Korhonen et al., 2018). Solarmaterials can create value from what was previously considered waste by applying the CE framework. With decreasing stocks of CRM, the demand for recyclers will rise tremendously. The raw material value of disposed of PV systems is estimated at $2.7 billion in 2030, opening a new market for recycling companies such as Solarmaterials (Rystad Energy, 2022). Moreover, their technology will increase raw material value by 150% from 250€ per ton to 620€ per ton (Solarmaterials, 2022b). With a rising CRM shortage and increasing dependency on single countries like China, the rest of the industry will be highly dependent on their ability to recover materials to remain profitable and competitive in the solar industry and relative to other REs.

V.1.3 What limitations arise?

There are several obstacles in the EoL stage, ranging from technology to capacity over legislation and collaboration. First, recycling photovoltaic systems encounters several physical limitations that require technological innovation (Korhonen et al., 2018). Current recycling technologies are either unable to recover certain materials at all, lose quality on the way, or are little economically feasible. Solarmaterial's innovative recycling technology promises to solve some technological issues, but their profitability has yet to demonstrate itself. Second, while there are initiatives to coordinate the disposal of PV modules (PV Cycle, Elektro-Altgeräte-Register), there are few specialized recycling facilities. The recycling volume is insufficient to supply the approaching waste volumes (Appendix J.I). Also, that of Solarmaterials is still very small but offers the potential to grow. Third, gaps in regulations and policies do not respond to these limitations and, therefore, are not supporting CE Principals. In the WEEE, the weight of the recovered material, not the type of the material, determines the recycling goals (WEEE, 2012). As a result, the heaviest and simplest elements tend to be recovered rather than the more critical and precious resources (El-Khawad et al., 2022). Last, the recycling industry must adapt to various PV system technologies (e.g., c-Si-technologies, CIGS, CdTe). Considering the life span of a PV, a recycler has 30 years to adapt their technology to the new design of a PV system. While this provides them with a proper planning period, it is inefficient to adapt to new standards frequently (Appendix J.II). Especially as only a small number of PV modules are designed with CE principles in mind.

V.2 Enpal – Circular Services extending the Use Stage

Enpal is a provider of PV rental systems for private houses. The company was founded in 2017 and is now Germany's largest provider and market leader, with over 6,000 customers. Enpal operates according to a solar-as-a-service (SaaS) business model (Bath, 2021; Carnegie, 2022; Nowak, 2020; Pv-magazine, 2020). Enpal rents out solar systems, electricity storage, and wall boxes supplemented by a green electricity tariff and networks them into an integrated overall solution. Their business model handles the planning and simulation of the system, installation of components, maintenance, repair, insurance, monitoring and supervision, replacement of defective components, and replacement of the power storage system (Enpal, 2022a).

V.2.1 How do they support CE?

The challenge in the use stage is to create incentives for adequately maintaining the PV systems, also because public perception of second-life modules is not very favorable (Tsanakas et al., 2020). If an installer's responsibility ends with the assembly of the modules, the decision-driving aspect will mainly be the investment (Appendix J.III). The prosumer will decide on the cheapest system not considering the module's durability. The setup for following up on the system through its life, including repair and preventive maintenance actions, is not in place. The prosumer often lacks the knowledge, incentives, or opportunities to create the circularity of the product (Bocken et al., 2019). Enpal's SaaS business model is improving CE aspects. Enpal, as the operator, retains ownership of the product and lifecycle responsibility and offers the products only as a service (Enpal, 2022a). Customers can then subscribe to the product and pay recurring fees. The customer can benefit from easier access to their needs and products without having the barriers and challenges of ownership. The model incentivizes Enpal to maximize resource productivity and lifetime value. While selling ownership incentives to produce at the lowest cost possible and using cheap materials, and minimizing their input, the shift of ownership leads Enpal to focus on the lifecycle of their products and think about potential reuse and recycle options (Bocken et al., 2019; El-Khawad et al., 2022).

V.2.2 How do they benefit from a CE?

Enpal's business model is a lockstep model, showing a positive correlation between positive impact and profit. They will be more lucrative if they install long-lasting models and repair and maintain them. For them, the SaaS model will lead to a better customer relationship, as the interactions with the customer do not stop after the purchase. Till now, their contribution is not clearly part of their employer branding. If they present their contribution to CE more clearly to the public, this could bring further advantages for corporate attractiveness and market positioning.

V.2.3 What limitations arise?

Due to the aforementioned physical limitations and the current state of research, CE principles will delay but not prevent the EoL of products (El-Khawad et al., 2022). Therefore, CE implementation is crucial at the use stage to prolong the cycle. While Enpal's business model creates great opportunities to further implement CE principals (R3-6) in the use stage, it also has its weaknesses in practice. Usually, the providers in Germany have a contract period of about 20 years and sell the product for very little money to their customers afterward, including Enpal selling for 1€ after 20 years (Enpal, 2022b; Sunvigo, 2022; Yello, 2022). The expected lifespan of a PV is 30 years, exceeding their service by ten years. In doing so, they secure their profits and competitiveness but relieve themselves of the responsibility of managing or delaying the EoL phase during the critical years. Moreover, German legislation interferes with the extension of the use phase. Before January 1 2022 the Feed-in tariff period for a PV module would expire after 20 years, making it unlucrative for prosumers to keep their PV modules. With the change in legislation, these conditions have been improved, preventing both the dismantling of the plants and illegal feed-ins (Energie-Experten, 2022). However, the conditions for prosumers selling their electricity to the network operator remain unattractive (Solarenergie Förderverein, 2022).

V.3 Solarwatt – Designing Circular at the Fabricant Stage

Solarwatt is one of the leading German manufacturers of PV systems which range from solar modules "Made in Germany" to intelligent energy management and storage systems for residential and commercial use. The company was founded in 1993 and now has over 700 employees (Solarwatt, 2022). Solarwatt is one of three German manufacturers and has a production capacity of 300MW. Thus, Solarwatt is the producer with the lowest capacity among the German manufacturers: Meyer Burger has 400 MW and is planning to expand to 1.2 GW, and Heckert Solar has 800 MW (ITRPV, 2022). Solarwatt produces with 100% green power and offers their customers the possibility to offset emissions further. Their glass-glass modules meet the Cradle-to-Cradle (C2C) certification, an independent and globally recognized CE standard (SolarWATT, n.d.).

V.3.1 How do they support CE?

First, Solarwatt serves as a role model for CE in the solar industry as they apply CE principles in their production. They are the only German manufacturer and one of only three manufacturers worldwide to meet and hold the standards for the C2C certification for their modules (SolarWATT, n.d.). They set an example for sustainability in a very price-sensitive industry, changing the perception of consumers and industry stakeholders (Appendix J.I). Second, in Germany, glass-foil modules have become the standard in recent years. Glass-glass modules, in comparison, are more robust, durable, and efficient. Their lower popularity stems from the higher initial cost and, in some cases, more tedious installation. Therefore, the glass-to-glass module is more favorable from a circularity standpoint (PV-Manufacturing, n.d.; SolarWATT, n.d.). In addition to the general better suitability of the glass-glass modules for CE, Solarwatt's modules further comply with the circular standards of C2C. The C2C certification considers Material Health, Circularity, Energy Management & CO_2 Emissions, Water Management and Social Responsibility. Worldwide, only three PV manufacturers have any certification at all (C2C Certified Products Program, 2022; SolarWATT, n.d.). Third, while their production in Germany does not apply CE strategies directly, it clearly aligns with the first CE principle. A significant number of solar panels are imported from Asia to Europe (Franco & Groesser, 2021). While the transport to Europe only accounts for three percent of the total emissions, the energy mix in China is causing issues (Storch, 2021). According to the Fraunhofer Institute (2022), 40% of CO_2 could be saved through a production in Europe. Solarwatts Germany-based production, only using renewable power sources, is therefore saving emissions in comparison to most installed modules and creates independence. In the future, Germany might get into a predicament being dependent on China producing solar panels with a capacity of 53.000 MW in 2021 alone but only covering a recycling volume of 10 MW (China Dialogue, 2022; GEIDCO, 2021). In addition, Solarwatt's production volume should also provide the ability to convert that volume to recycling if necessary (Appendix J.III).

V.3.2 How do they benefit from CE?

Firstly, due to the robustness and the long warranty promise for the systems, Solarwatt will generate greater customer satisfaction. With its clear focus on sustainability, Solarwatt answers to those customers who want to make climate-conscious decisions and can therefore establish itself in this market segment (Appendix J.III). Secondly, German legislation forces manufacturers to recycle 80% of the electrical waste they are generating, with plans to increase this percentage in the coming years further (Appendix J.II; WEEE, 2012). By designing their products circularly, they will be able to hold up to this more easily and cost-efficient. Sustainable design and the increased ability to keep materials in the loop will benefit manufacturers and their economic durability enormously in the long run. Due to the scarcity of raw materials, their prices will increase significantly, affecting the competitiveness of solar energy compared to other REs. By adopting a circular positioning earlier, Solarwatt can gain an advantage over other PV manufacturers that reach this understanding later. They will not need to rely on change management, which studies show to be complex and lengthy, to adapt to new market demands and by being an innovation surrounded by a network with design experts and recyclers (By, 2005).

V.3.3 What limitations arise?

The circularity of the fabricant stage is underrepresented in the literature compared to the other stage (CSA Group, 2020). The current goal of this stage is short-term: the required capacity for PV plant production volumes must be achieved, and this must be done as cost-effective and efficiently as possible (Appendix J.I). PV panels were only included in the WEEE in 2012 (PV CYCLE, n.d.). It will be some time before solar modules designed for reuse, repair, refurbishment, and recycling take over the market because the industry did not have sufficient time to adjust (El-Khawad et al., 2022). The number of manufacturers with C2C certification shows that CE is not a priority at this stage. Only manufacturers with an above-the-norm focus on sustainability consider this. Moreover, the example of Solarwatt shows that circularity also has its disadvantages. The production of sustainably designed systems is more cost-intensive and complex (Interview X.III). This could also be a reason for the comparatively low production volume. In order to meet the goals of the ET and to guarantee the security of supply, a sufficient production volume is necessary, which might not be achievable with CE-aligned fabricants only. Furthermore, manufacturers are dependent on many different suppliers, such as wafer producers, making it difficult to guarantee a supply chain designed for circularity. In the end, only a single component is designed for circularity.

VI. The Journey Continues – Cross-Case Analysis

This study draws on an analysis of several case companies operating along the life cycle of a PV system to investigate and improve its circularity. The three case companies show how circularity is applied in the life of a PV plant. A recycling company that manages the end-of-life of a PV system, a rental model that promotes the extension of the life of a PV system and a CE-friendly production method for individual components were examined to determine how they contribute to CE, how they benefit from CE, and where limitations to achieving a CE lie in their current area of operation. Solarwatt, as one of few manufacturers worldwide, designs its modules with CE in mind. Nevertheless, even here, for the time being, it is only one component and not the entire system.

Generally, if not concentrated on truly maximizing their sustainability, fabricants are little aligned with CE principles. Recyclers, on the other hand, are by their nature circular. Solarmaterials clearly aligns with CE in their mission and business model. However, their recycling capacity is small, and the cost-effectiveness of their technological innovation still needs to prove itself. In the use stage, SaaS businesses are a significant contribution to CE. Enpal supports CE by the nature of their business model, but it does not reflect their active orientation, which can lead to failures in significant moments.

Through a comparative analysis, it becomes apparent that each stage faces limitations on different dimensions to truly close the loop to a CE. At the EoL stage, the biggest limitation is technological advancement. Future research should investigate advancements in recycling methods to recycle more materials with higher quality and scale-up opportunities to guarantee the economic viability of recycling standards. In addition, the infrastructure for innovation should be fostered through entrepreneurial ecosystems and additional monetary allocations for hardware solutions. The limitations of the fabricant stage are of a political/economical nature. Implementing CE principles means an increase in costs in the short term, threatening the manufacturer's competitiveness in the highly competitive solar energy market. Only legislation could provide incentives. The biggest limitations for integrating a CE on the use stage are economical/socio-cultural. The public perception of reused material signaling lower quality and the higher cost or the potential of efficiency omission of aligning with CE hinders its implementation. Implementing a CE framework creates new business and job opportunities at each stage and will lead to financial stability, considering rising prices for raw materials. Due to the lack of interactions between stakeholders in each stage contributing to a truly sustainable ET, issues are solved only in one stage, shifting difficulties to other parts of the lifecycle (Appendix J). Due to the lifespan of a PV, monetary investments made today are locked in for the next 30 years creating carbon lock-in effects. To truly align with CE, stakeholders should interact with other actors in their stages and outside. Each stakeholder is the expert on one stage and, therefore can influence material and design innovation through knowledge sharing. The lack of circular design can be attributed to insufficient collaboration between different stakeholders of PV plants. While fabricants indicate that they actively listen and consider recyclers' voices and advice (Appendix J.I), recyclers often do not feel heard (Appendix J.II). Instead, fabricants should work together with recyclers to develop recycling-friendly modules. For example, reducing the amount of material input presents an advantage for the manufacturer through reducing costs and resource bottlenecks but creates disadvantages in the recycling process during the EoL stage due to making the extraction more complex and challenging. Through collaboration, it could be estimated which trade-off is worth taking for the overall gain. A greater dependency between stakeholders is to be expected. RE technology recycling must be one of the fastest growing sectors of the next years, changing the imbalance between large, dominant manufacturers and small recycling start-ups.

VII. Conclusion

To conclude, the potential of the solar industry is significant, but its shortcomings in terms of negative environmental impacts should not be ignored either. Considering climate goals, the question arises whether it can be afforded to create this problem first and solve it afterward. Successful measures to implement CE in the German solar energy sector are taken, which show to improve stakeholders' economic and competitive viability, especially concerning the future. Active purpose alignment often leads to more initiative and momentum. Therefore, players in the solar industry should take preliminary measures to align both business model and mission. 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.

6 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.

7 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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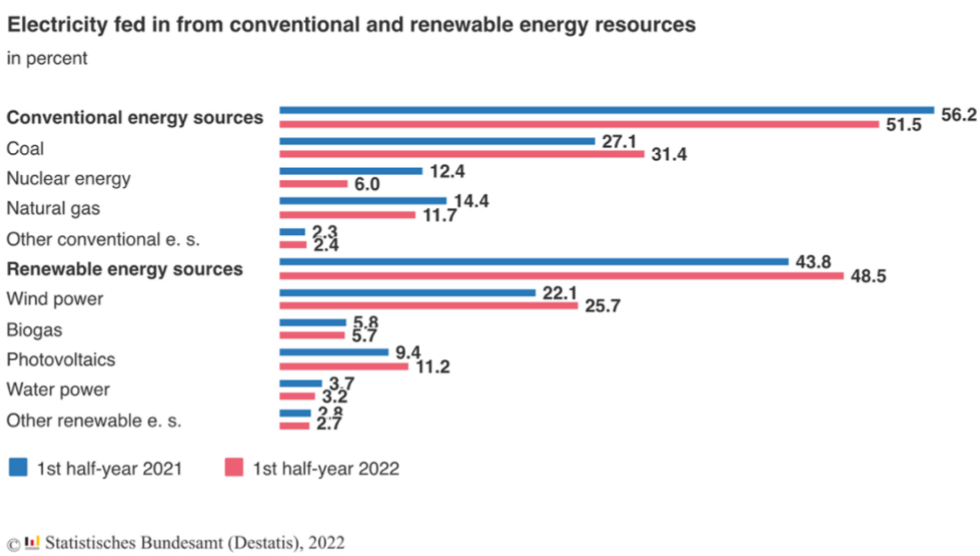
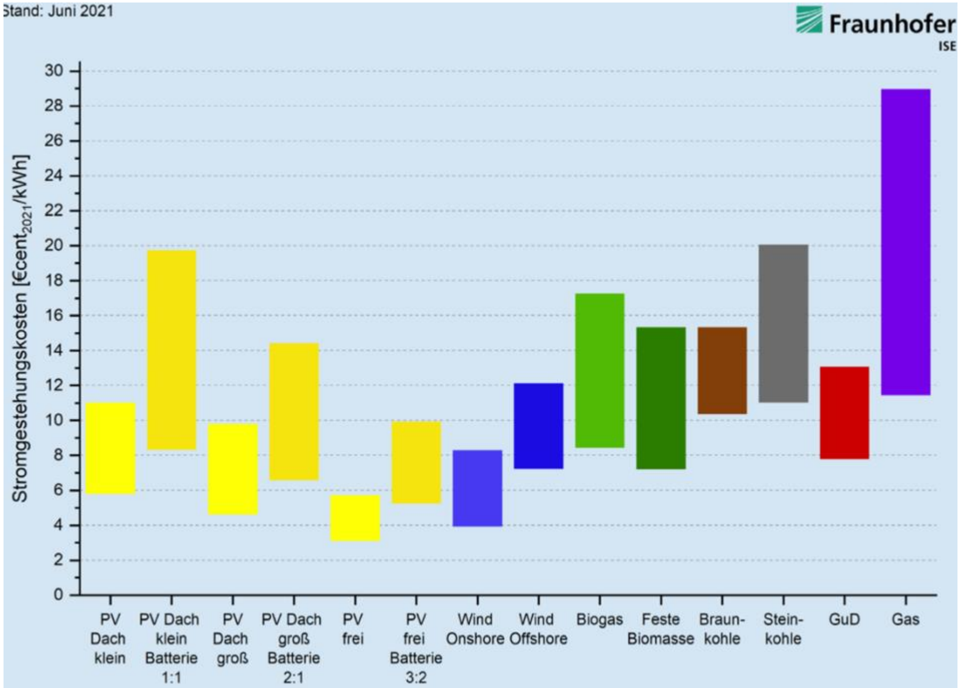
9 Appendices

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



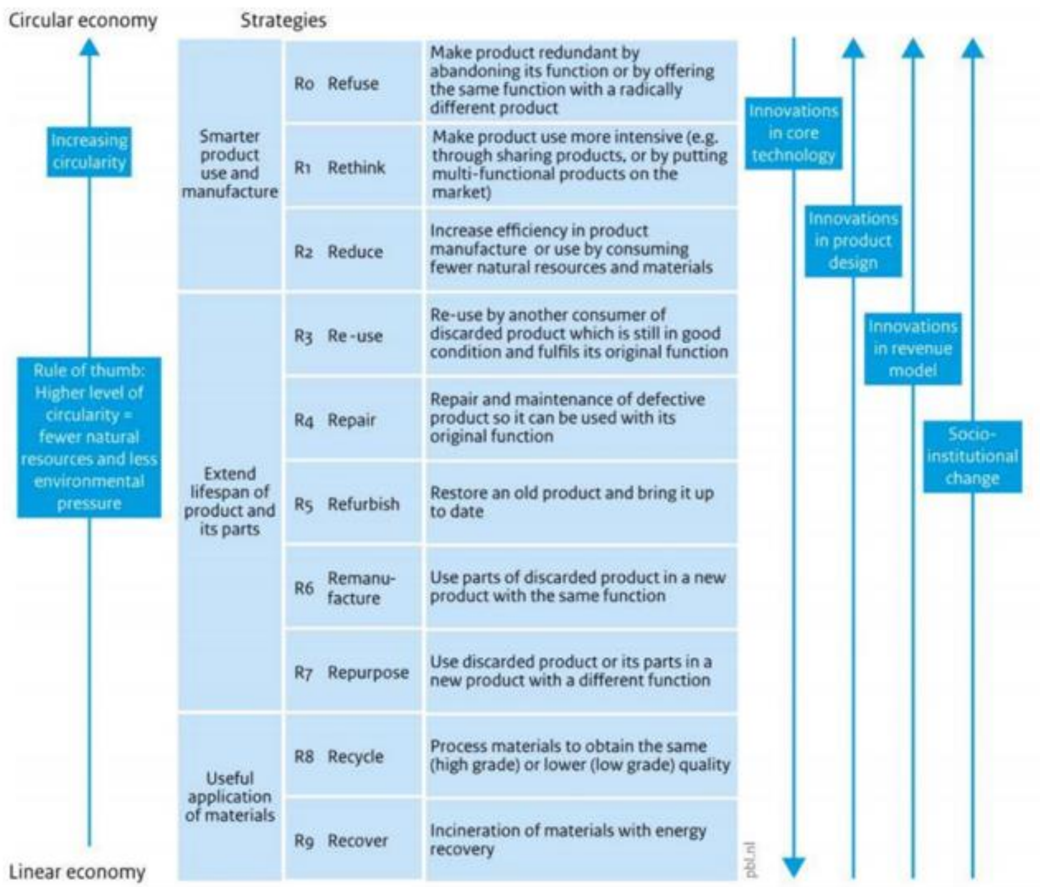
Source: Fraunhofer ISE (2015)

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)

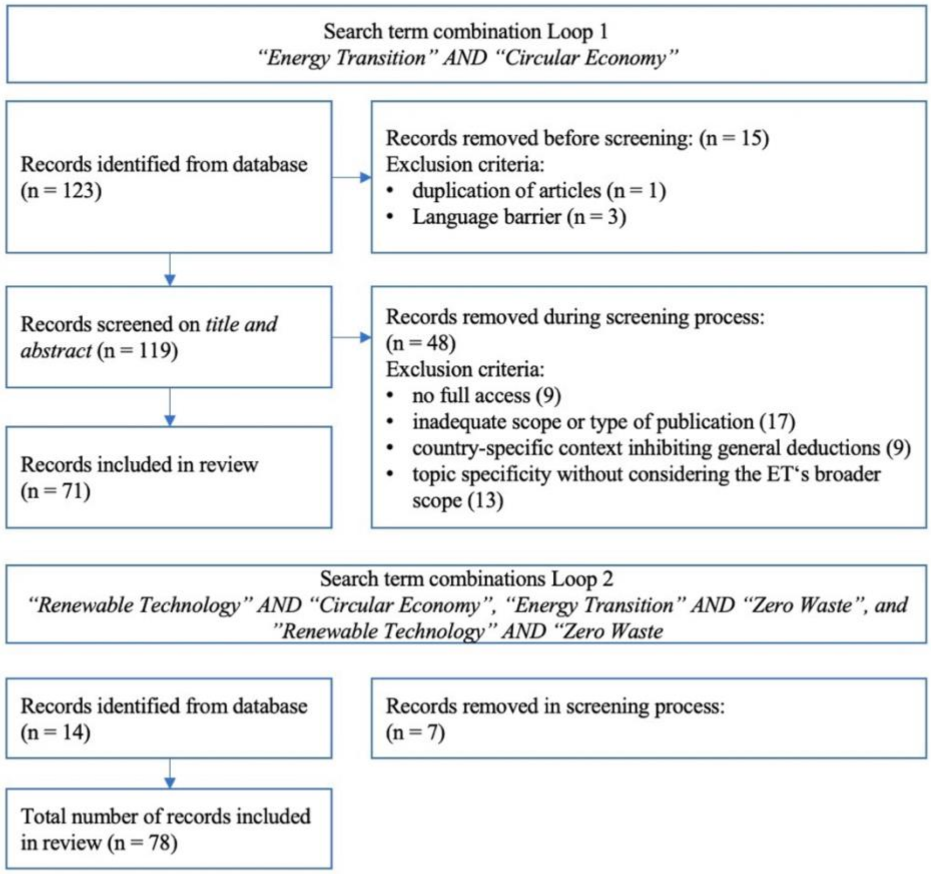
Appendix D: Descriptions of the 10 R's and categorization into respective stage of the CE



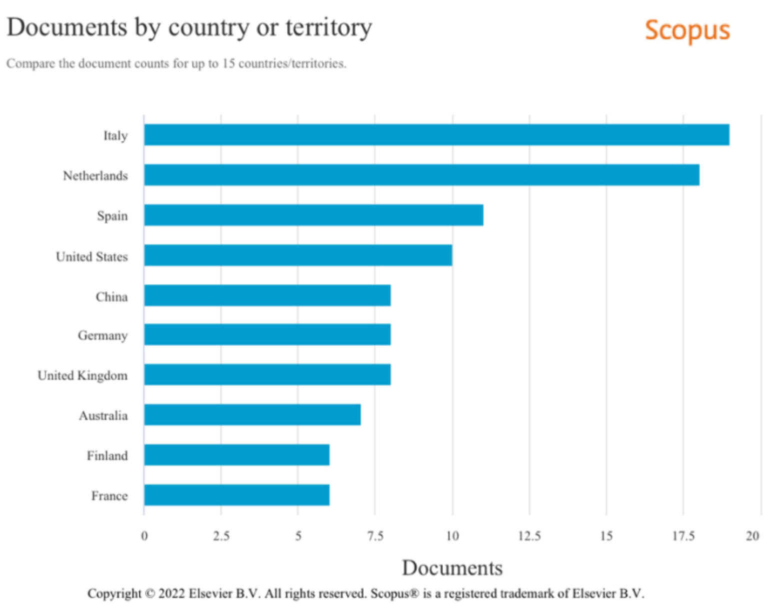
Source: Potting et al. (2017), Figure 1 : 5

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
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

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."

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."

						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

	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."

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."

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."

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 environ-mental 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."

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-recy-cling 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."

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 Dębiénsko 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."

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

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."

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

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 I: Circularity of the German Solar Energy – Case Studies along a PV's Lifecycle Stages

Appendix I.I: Transcript of Expert Interview 1

Interviewer: **Sina Distler (**hereinafter **SD**)

Interviewee: **Head of Innovation, PV Manufacturer (**hereinafter **E1)**

Date: 08 - 11 - 2022

SD: So, it's about me writing my master's thesis. We are writing in a team of five people. And it's about the alignment between Circle Economy Principles in their Energy Transition with the focus on Germany, which is the main topic, the systematic literature review. And broken down it is now so that each of us again focuses on something specifically. wWe now have a total of five focus areas and mine refers to solar and PV plants and there I look at how CE Principles are considered on all four lifestyle stages, so in the design, in fabricant, the use and in the end of life stage. And that's exactly why XX is a perfect contact, because you play a super important role in the design and fabricant stage. And that would be the introductory question, what exactly is your focus and to what extent do you include Circular Economy principles in the design or factory stage.

E1: Yes I can to that. Is it okay if we switch to English?

SD: Sure we can.

E1: I can give you more information I was previously working for Fraunhofer Institut for many years. So, I have a little bit of information und this is a very important thing. Not related to module manufacturing, but it is a very important topic. So, first regarding the strategy point of view – generally you see the crisis in Europe and this crisis that we are at moment in with energy transition is the fault of Europe in the beginning because we were dependent on the other source of the energy. But in the mean time because of the not proper policies, the big solarpanel manufacturing in Germany went insolvent and therefore we do not have big local producers. So, the same thing which is happened to the gas with Russia can happen to solar. Because we are the dependent on Chinese solar as we were dependent on Russian gas. So, we ourselves also have a production site in China, because the whole supply chain is there. We should consider that the whole economy should come to Europe – not only the module or cell manufacturer. To your question, solar energy is the cheap energy source that you can find on the earth. It's cheap than all of them by far. Considering the renewables you can also say that this is a perfect choice, because you have less maintenance cots you have less initial investment costs and you have a lower levelized cost of energy. The levelized cost of energy is when you have your initial investment. You have your degradation, your maintenance costs and your operational cost. When you calculate this you have the net cost of energy for a timeframe of 30 years. This is very important that we should consider a range not on point. And this is what is very important to consider. At the moment Europe is targeting for 1.6 TW. So this is a word to say, but the point is that how it's going to be down is a very difficult thing because first of all we don't have the European factories which can produce it and second of this European factories still get the material from China so we are still dependent and third of all is the question where are we going to install it. So 1.6 TW is not a small amount. That means you sometimes need to think about other innovations, like using them in frams farms together with agriculture, so agrivoltaic. You can put it into buildings or think for example in the autobahn or something like this. So that you integrate more and more. This is the policy making I would say, rather than a technology push-through. So for module manufacturing this is not a big concern, as I said, the only big concern is that the whole supply chain comes from China to Europe.

SD: Okay, ja.

E1: As it was before.

SD: Just a follow up question: PV's are using critical raw materials, one strategy to become less dependent is than to consider recycling options. Wouldn't it make sense to also integrate recycling perspectives in the manufacturing? I talked to a recycling company before and they say that very little comes from manufacturers and they do not expect them to adapt.

E1: This is totally wrong, but the point is nobody really thinks about recycling the modules we have a lot of trash and this trash should be recycled because inside it we have silver and the glass can be also regenerated, reused and aluminium, we have a lot of aluminium frames. The point is it's not always too, I mean if you want to go and buy an Adidas T-shirt from the recycled material it is more expensive. This is a problem the module manufacturers think about. Actually today it was funny that we submitted one project that we make a module frame from recycled materials okay this is Violet project that we have submitted together so we are open to use these things because we already think about using recycled material in the PV modules. The point is that it is not cost effective because if you want to for example recycled aluminium you cannot use the whole aluminium which is there you have to put one third of the new product as the recycled aluminium. And you have a lot of energy to consume. So, at the end of the day you see we'll have a bigger carbon footprint compared to your initial one. I just want to say it might be at the end not that much more environmentally friendly if you think about that in this way. However, in case that you change the concept, for example, you want to use polymers then there is something which can be used. Or for example think about windturbines they are they are from chemical fibre and last forever polymers and you cannot really recycle them. So, when they're trashed they are really trashed. But now we're trying to think to reuse them also in PV but this is like confidential project. But it is showing that we are going in this direction but the point is that this product might be too expensive, so this is older in the future unless that we get more policies and supports the big companies or the customers are obligated to use recycled materials then from our point of view it's a great chance and so module manufacturers are conservative but at least in XX we're not that conservative we're going in this direction.

SD: Okay, that's nice to here. Its also that I read that for example it is not only about reusing materials, like recycle materials in PV modules, but it's also about the design. Taking the component silver as an example: manufacturers try to minimize the material inputs to save money and use less critical resources, but that again makes it harder for recyclers to extract the material to than recycle it. Therefore, this point needs to already be considered in this phase. Is this something you do? And I mean it is always a trade-off between performance and progress.

E1: We can not put more precious material inside the module. The thing is that the PV market is a very competitive market and this competitive market the price plays the biggest role. Not a big role. The biggest. In case you talk to a customer and its slightly more expensive they do not want to talk to you. This solar cell is in a module [showing cell], it is a zebra solar cell. This is very elegant, but it is not yet a successful product because it is expansive because it has more silver in it. For us it makes no sense to put more precious material inside the module. All R&D is about decreasing not increasing it, they are even thinking about replacing silver with copper because you can make the model even more cheap and so this is not an option which can be a motive in the eye for recycling companies. The point is that there are two factors for recycling. First of all the security because if you put the solar glass on the ground and the water comes and it remains there for awhile okay there are toxic material in the glass in the glass itself not in the solar module because they add some chemicals that solar module glass has higher percentages of this chemical. If it goes to underground water a little bit is enough to kill 200 people. So this is a risk. The other thing is that you have to really think about I mean some people use like reusing the PV module they send it to like third world countries that they could use it although with lower efficiency, et cetera. But generally for the recycling and end of life of the PV module I actually never thought about the recycling companies. That how they're going to benefit ultimatly but still there are a lot of aluminium units and there are glass in it plus okay a little bit of silver at the moment but extracting that silver is still requires a lot of energy which at the end might not be even beneficial so this is something maybe a recycling people can add answer it better so in case you are interested I can introduced on people to you that they are working under recycling of the PV modules.

E1: It really does not mean at the end you have like environmental friendly system because you might to have even higher energy. Anyway this something that should be done because of the limited resources but I really don't know how it can be beneficial for the recycling

SD: yeah yeah I mean in the end considering economy principles recycling is the last one you should take because it's the furthest from a Loop. Firstly you are trying to rethink, repurpose, repair. It this stuff if there's also something for example you consider in your design phases like how good it is being repaired in the end if like adaptive models or something are an option?

E1: to a small extent. We as module manufacturers are dependent on raw materials. So I am dependent on the backsheet, which is produced by the backsheet manufacturer. Not by me. So we build obtain the material. The circular design therefore is dependent on the component manufacture not the module manufacturer. So for us, the best thing we can do is to use materials that are recycled or can be recycled easier. If it is already recycled this is something we already use. I can show you something. We submitted a project. I will share my screen. This is a new project we have. […]

SD: Does this project has something to do with the legislation that manufacturers need to recycle 80% of the materials?

E1: It is not a must to us. It also cannot be a most to us. Look at how manufacturers there are in Germany with their capacity. So you basically do not have any one. If you make rules for someone, there also should be someone. Additionally, we are in the middle of a crisis. So, it's a different focus, all about bringing more installations. And again we are coming back to policy. Because the policy is the most important factor here. But most of the time their policies are non sense. The rule should make sense, not for example through making the product more expensive. Because than you are no longer competitive. In the past they were over doing it so this is something they do not want to do anymore. But I see that I need to jump to the other meeting.

SD: Thank you for taking the time […]

Appendix I.II: Transcript of Expert Interview 2

Interviewer: **Sina Distler (**hereinafter **SD**)

Interviewee: **Founder, Recycling Start-up (**hereinafter **E2)**

Date: 02 - 11 - 2022

SD: I'm writing my master's thesis on the alignment between circular economy principles and the energy transition in Germany. All in all, there are five of us and so far we have done a comprehensive literature review to find out what the issues are, where the gaps are and where there are already solutions. And now we are looking at certain areas individually. And there is my area solar, especially in connection with PV. The subject of the analysis will be that innovation in this area is always advancing and that it is happening very, very quickly. We cannot start and simply plan the solution from the inside, from the beginning to the end. We have to use every lifestyle stage of PV systems and do it simultaneously in order to achieve a sustainable energy transition. And that means that we start at the design state of the fabric in state of the state and at the end of live stage. And you are particularly interesting there, because once with XX but also with XX you are the experts on the end of life stage. And with that, I would perhaps also start and ask you why you have focused on the end-of-live stage and where your problems are and how you solve them.

E2: (...) Exactly. So what was decisive for us to focus on this is that if solar energy is to be a sustainable form of energy, then it also means that the value chains must be built sustainably. And part of a value chain is also recycling. So this is the missing component, where we say that a holistic sustainable energy also requires recycling. This means that we have focused on recycling as such. Of course, I always have technological challenges, but there are two issues in particular. One is the supply of solar modules. So there are estimates that dictate that modules have to be recycled. How do they have to be recycled? So how is it sort of regulated what has to happen with end of life modules? That's a big aspect, that you actually get the modules into the recycling. And the second aspect is that there are, of course, a large number of modules that are all similar, but ultimately have different structures. Which of course makes recycling always challenging. But that actually applies to all types of recycling. Let's take the yellow dot, for example. There I also have the issue. I have super many different plastic types in a recycling stream and exactly that we also have super many module types in the recycling stream and of course we always have to react technically to that. That means we have the two aspects regulatory and variety of modules.

SD: Exactly with the Regulations it iscurrently so that it goes only after weight. So, it is not based on the distribution in the sense of the value of the material. If this could be implemented, it would be something that would benefit you by focusing particularly on critical materials such as silver.

E2: Under the planned new version of the legislation, it will be based on the components, the raw materials, and will no longer be pure weight cycling. And that, of course, plays into the cards.

SD: Exactly. And with what you mentioned, with the different structure of the solar plants, that makes it more complicated to recycle them. Later on, a bit of this Live Stages approach, because it's about getting in touch with the Design Stage or the Factory Stage, for example, to do research publications. After all, you are the recycling experts who could tell the manufacturers or the designers of the plants how it would work as simply as possible for you to recycle the materials in a very sustainable way. Are you already in contact with different design or manufacturers of PV systems?

E2: That's exactly what we're already doing. It's difficult, of course, because the majority of value creation and production takes place in Asia and, of course, these companies are also very large on the other side, so they're sluggish and don't share the information. For example, no one wants to disclose information about the individual components of their modules because they are usually company secrets or what makes them special. This means that it is difficult to obtain this data. On the European side, it is somewhat easier because the companies there are more open and also, let's say, the legal area is different. Currently, we are explicitly dealing with this topic in two research projects, i.e., together with module manufacturers, we are looking at what is in it, what does it mean for recycling? And then we are also looking at how modules can be made recyclable. But that is more a point that would be nice to have. At the moment, I don't believe that this will really be reflected in the end.

SD: You think it won't be reflected because then the manufacturers won't adapt the new forms, or what?

E2: Yes, exactly, because in principle I then have to react to this as a manufacturer and perhaps adapt my production processes, which entails costs, which perhaps also leads to the fact that things are perhaps better recyclable, but then in the end the unique selling proposition for this module is no longer there, because one says I had to exchange material or so, that is, actually it is so, I can give two tips, I can still give hints. But I think it is questionable whether they will be taken to heart.

SD: Of course, that's a bit of a sad prospect, especially when you're working in an area like the energy transition, where everyone should really be pulling in the same direction. That's also where a bit of another question that I had, like you guys with it as well, for example, comes in. In the Performance in Progress thoughts addressed that you want to be sustainable on the one hand and on the other hand not and so or not sustainable, but that it just represents difficulties, because you then always have this trade off between. So, I'm doing something good and it doesn't pay off financially in terms of benefits. And in the social economy, recycling is the last principle to be applied, which is almost the closest to the linear economy. So it's practically the end and then you feed it back in again because you renew it. Do you have any conflicts or potential conflicts with that? What it then concerns for example if emand for example on the Use State the solar plants as long as possible in the process holds. Is there an optimal useful life in recycling or does that not matter at all, for example? Does that somehow conflict there with the quality Recycle and Relocation or similar?

E2: (...) Um, so what you have to differentiate, first of all, that I am actually legally obligated as a recycler to check my Second Life capability. That means that it is also a process that is planned and included in our company, which we are currently working on. Because, of course, the goal is to only recycle what is really end-of-life, i.e., what simply has defects, etc. And that's where I come in. And even with that, I reach my limits, insofar as I always have to react back to the multitude of modules. What can I install at all as a component here new or can I guarantee there also with justifiable expenditure not only financially also resources sided at the moment? Of course, it's more exciting to say that the companies that put the modules on the market can also offer the modules again because they know what's in them. So that also happens, um, I'll say, to be able to return to the original state. That is actually the goal at the moment, where I would say the journey can go. Our goal is also at the end. In theory, it doesn't matter to us how long these things remain in operation, because at the end of the day, at some point they will be technically out of service and then we will get them back. Whether that happens now or later doesn't really matter. Especially because we also said that we might even consider recycling as part of our business model, because we get these quantities. And so it is then also a part of the value chain for us. So we have then at the end we would have several revenue models once, where we say, clearly, the recycling as such, but before also already the utilization of the Second Life modules, so the resale of the modules, also maybe a film like an arrow. That's not saying we're competing, we're just saying hey, we're recycling these things. And if we have good ones that still work, you might be able to realize them more cheaply. So that's basically more of a win win than just kind of a problem.

SD: But then it's exciting to see that there's a bit more of an exchange between the Use State and the End of Live Stage, whereas with manufacturers you tend to have a bit of a competitive mindset.

E2: The so perhaps also again supplementary to the recycling question. The goal is of course always to say if I, if I would get that with refurbishments. Of course, it's preferable to recycling in the first place. On the other hand, I also try to recover the raw materials in recycling in such a way that I can avoid the primary raw materials, so that I can also deliver a product that is comparable in terms of quality and then go back to conserving resources. That is really what the activities or efforts are aimed at.

SD: Yeah okay, great. You mentioned it. That is then on strives that one feeds only defective solar cells really then into the recycling process. I have read in part that this is also a problem, but it represents when they are defective, for example. There it is just much addressed to glass. Does this also apply to you and how do you deal with the fact that this is then also a bit of this it must not be too broken.

E2: (...) It doesn't matter to us for now. So what we work with in our recycling processes, whether the glass is broken or whatever, doesn't matter. So the process works with all modules. The limits that we have with us are mainly in the deformation of modules, as if it is a module simply bent. So the whole aluminum frame is bent. Then I have difficulties with handling, because then I can't put it on a surface anymore, etc. Then it becomes difficult. We can't handle the modules, but it's a fraction of the modules that actually come back. And there, too, it's a bit of a goal to look. If people have an awareness of refurbishment and recycling, then they will handle the modules better. So if I say I don't care what happens, then I can just throw all the broken modules into a container. I don't care how they fall in, and then they are bent and dented and we can't do much with them anymore. But if I say, hey, there might still be Second Life capable modules in there, I can test them, etc., then you might get some money. Then you might get some money back. For your recycling, I have a different incentive to get the modules to the process really well. And it's not as if all problems can be solved with one technology. That means we can cover a large part of the modules, but those that are completely deformed will probably continue to be shredded and sorted. That this is the standard.

SD: Okay, very interesting. So this would also offer a super potential for you to cooperate with repair services, for example, which already have the repair process and you then go into the exchange in order to then, if this should somehow end, then comes into question for you. Basically then maybe again to, because so 2025 to 2030 probably comes a relatively large amount of PV on us, because just there now 30 years ago the first time was the large expansion. And you are now, for example how do you assess your potential to tackle this and how do you see your Scaling Up?

E2: Um, the problem with hardware-based or technology-based business models is that scaling is capital-intensive. So if I look at a software startup, for example, it scales more or less exponentially because it usually has recovery revenue and then that always comes on top. In the hardware tech area, I have more of a linear relationship. That means that if I want to recycle a module, I need a piece of plant technology. So I can't scale up as quickly as I want, and I can't grow as large as I want without further ado. What we have set as a goal is actually to say that what PV what is coming back now. Currently on the capacity side I don't have quasi commercial. The only thing I could do would be shredding, sorting. There is market leader in Germany, the company Rei Link, but even they are then with what they have and what they would plan, not able to accept everything. That means that our expansion speed is primarily determined, I would say, by the organization and capital side than by the market side. So it will probably be the case that this tsunami of what is coming at us will at a certain point be greater than what is already there in terms of capacity. And then it will level out a little bit over the years. But I would say that it's a bit like that, we are now aligning our, our growth more to what we can achieve in terms of organization and capital, although we know that the market would probably give us much more.

SD: One question about investments. I mean currently it’s anyways a critical time. Generally Green Tech does not suffer to badly, from what I heard, but still. How is your experience with investments currently ?

E2: No, not yet, yes, if it is not a problem um. Difficult. That's the wrong word. It was already difficult before, because hardware and tech are always more difficult to finance than pure software themes, because they simply have the scaling theme in them. So, that means many impact funds or even green tech funds define simply because they have to deliver performance on the revenue side, just often continue to rely on software-driven business models or service models. And that's the way it was before, and it's still the way it is now, which means that it was always much more difficult to finance products that have technological risks and are capital-intensive. And that hasn't changed. I would say that what has changed is that the demand is greater on the investor side, so that we are having much more discussions, because there is much more interest in tackling impact solutions, tax solutions, but nevertheless this is not always done with the investors, because they simply say okay, linear growth in quotation marks is an exciting market, but for me this is not the leverage on the capital that I have had so far and with which I can continue to drive returns.

And you'll probably know that as well, then from this startup world, from the investor world. That hasn't changed much now. So hardware is still difficult.

SD: Yes, does much of your work involve state support? So that somehow a state foundation, yes somehow seen that environmental foundation or environmental foundation with you somehow hangs in there, she then is there then rather the investor or is that then so a bit the mix of both??

E2: Of course, the primary goal is always to cover the capital side of the company through pure venture capital. Anything that can be added on top of that, or that reduces the financing requirements, is a goodie, so to speak. That means projects with the German Federal Foundation for the Environment, other research projects. That's the side that, when you talk about the state and capital, flows back to us in quotation marks, where we say, "The funding opportunities for such topics are of course very good and up to date, and that benefits us. But there is little real state capital in the sense of federal capital at the federal level. Of course there are KfW funds, but they mostly do fund investment. That means that we are actually back on the classic venture capital side and I say the government side for the funding landscape. Yes, for the funding definitely. Whereby we can no longer plan and not bet on it. Can that comes. So, as I said, it's just a building block that is then on top or that could then maybe replace something if it's safe. And the state capital, which is then more interesting for us, is on the scaling side. If I now say that I have already built two plants and can show that these plants are operating profitably, then it is relatively easy to finance the next expansion with a bank and with a bank guarantee from the country, whatever country. So, then state capital becomes interesting. But this phase up to then is actually no man's land and that is still a big, a big problem

SD: Yes, okay, that would be exactly that. So I've also kind of noticed that in my work environment, money is one of the big dimensions, especially when you're in that in-between stage between pre-seed and scale up. What are the limiting factors for you?

E2: If there is, then it's a matter of certification, approval, logistics. So I simply have large quantities of flows or volume flows that I have to move in different directions. That means that the necessary knowledge or network is something that we can't map out in-house and, of course, the certification issue. We started out as a technology company with research and development, and now we have to take the step to recycling. Companies need permits, locations, etc. for this. And that is something where we are also dependent on partners and, of course, on authorities or approval procedures..

SD: Yeah, okay, and then I'm almost through with my questions. Thank you very much. Maybe you can just give me your personal assessment of where we're at. So, what is the status quo? Because it's often a little bit unbalanced in the literature. There's disagreement on how far you've really progressed with a sustainable, really a clean energy transition. Where does solar stand? Gladly in comparison to batteries and wind.

E2: (...) So perhaps with regard to PV, I think Germany is still underdeveloped in this area, if you look at the expansion targets and what is being done, there is still a lot of room for improvement. Do we have to solve this through such obligations? PV must be installed on new buildings. I don't know whether such approaches will generate the necessary support in the end. It must be simply for each meaningful solution. And if I what one already notices is that I just by the energy crisis very, very strongly changes, so that many today consider and say can I make that, is that worthwhile for me? Hey, I have a cheaper electricity, but also there it needs mostly total package. So what is the point of a PV system, if I have quasi at the times where I have much electricity no easier but also generate and then little can feed and little remuneration. Kriege does not pay off, so I have to look, I have a battery storage? Maybe I have an electric car that I can charge. So I need this holistic concept so that such a sustainable strategy really makes sense. That's what I miss from you guys. And of course it's also a problem that it then involves much, much more investment until you somehow. I only need one plant or I only need one battery. That is, there I think you have to offer much more opportunities to also finance something like that, even as a private household. If you look at the recycling side, for example, it is quite exciting to see that there is a lot going on in the field of battery recycling, so there are a lot of big start-ups or even big rounds. But even there, there are actually no batteries for recycling. And the curious thing is, what we sometimes see is that we have the same situation with the PV topic. So we say, I don't have any modules yet, for example, or few modules. I don't. I also have little batteries to recycle. Nevertheless, the battery recycling issues are much, much more promoted and much, much already not promoted. Much, much more invested because the perception is different. Electromobility is in the perception. More promising, newer, more exciting than solar. And it's already noticeable that with that is the difference. If you look at Redwood Materials, for example. In the U.S. is in the start up in battery recycling. I think we are now valued at a billion. So we are bare on the solar side, we have nothing to offer there.

SD: That is actually very surprising, because as I now understood. I am now not very read in battery, but there the recycling works yes, so very, very bad in comparison. PV recycling is more advanced and therefore offers more potential. Where does that come from?

E2: But I think this storytelling is important because the topic of electromobility. Lithium ion lithium mining, availability, dependence on raw materials is much more present in the media than it is now. A dependence in the area of solar PV. And what is a bit curious is that we are discussing right now in Germany that we have such a great dependence on Russian gas. On the other hand, we have an almost one hundred percent dependence on PV modules from China. So if China would say now, we supply you to Europe, no more modules a prima. So you can bring it to the point and interestingly no one sees it or wants to perceive it. And it's a similar issue with batteries. There, too, we are dependent. But there the perception is somehow more real for the people than on the solar side.

SD: Thank you very much. I will end the recording.

Appendix I.III: Transcript of Expert Interview 3

Interviewer:	**Sina Distler (**hereinafter **SD**)
Interviewee:	**Project Manager at SaaS Implementation Project (**hereinafter **E3)**
Date:	9 - 11- 2022

[…]

SD: It would be great if you could shortly explain how the project is working and what you are doing.

E3: in my previous job I was working in the energy sector so it's the world I know a lot about but just so you know I can refer you to other people in the project with specific questions which would be would no issue. The project is focused on the idea that the value chain as it is working now is not really helping with respect to circularity. Currently how does it work for PV panels and for all the infrastructure that goes with them. So yeah typically a customer either private customer or company doesn't matter they buy the system - invest in a system. The system is installed and then okay there's the warranty. But that's what there is. I mean from then on, the installer or the manufacturer has little interest in the system and so you can only hope that at the end the owner disposes of it in a proper way. It's also not a setup that allows for following up on the system throughout its life and repairing it properly or taking preventive maintenance. I mean the user has no clue. What a user typically does is look how much energy the system produced and that's about it. So, it's not an ideal setup from a circular point of view. What we tried to advocate in the project is that a product service system is a better way of dealing with this kind of PV systems and what does that mean is that you typically involve either another party or that the installer plays a new role and he becomes the service provider. So instead of that the user buys and invests in the product an yeah takes over all the responsibility, the system actually stays the responsibility of the service provider or the installer whatever way you want to set that up. The benefit we believe that that ensures that at the install time proper choices are being made by the installer. Currently the installer has the drive to come up with the cheapest system available because there is the investment decision. If that means that the system has a shorter lifetime the installer doesn't really care and at that point in time a user is also not really inclined to take that into account. Whereas if the installer remains responsible for the system it is important for him that he installs a qualitative system that needs little maintenance that will live for a long time. Something I forgot to mention is that the idea is that there is sort of a service level agreement between the installer and the consumer, a sort of an energy contract, and as long as these panels are able to fulfil this energy contract there is no issue, and the installer doesn't have to replace them or whatever. So, he is at install time already inclined to choose a qualitative system with a long lifetime with little maintenance. Things like that also make improvements during the lifetime. He's very much inclined to properly maintain them, to follow up and by doing that extending the lifetime of the whole installation. Through the energy service contract the consumer can at any point in time choose to end the service even way before the panels reached their end of life but at that point in time the installer can also choose to install these panels on a different roof as long as they are still able to deliver the service level agreement he typically has with the customer. Nobody cares whether these are new panels or second life panels. We believe this way of working is very much in favour of a more circular way of working. Also at the end of life the installer has to deal regularly with systems that are end of life, knows how to deal with them as proper knowledge programme infrastructure. To deal with them he can reuse parts of it and properly recycle the other ones. Also, tha we feel is a sort of a guarantee for a more circular way of working and that's the model that we have tested in several demonstrators in the project both for PV but also for batteries that can be reused as solar storage. By testing this out in five demonstrators we've learned a lot. That's what we are currently distributing also towards policymakers because there are still quite a lot of specially policy instruments that are yeah not very well suited to this way of working.

SD: I've actually been talking with a German company whose doing like solar as a service I've learnt from them is that their usually renting-period is only 20 years and I mean this is usually how long a PV module anyways lives without any major complications and then after 20 years they would sell the solar panel for like a very small amount of money. Then I mean it's again the responsibility of the end consumer. Because then solar as a service company is just stepping out of the end of life responsibilities

E3: yeah really, that's right

S**D**: So this is finding a niche again OK

E3: And typically these panels will end up in a market where really cost prices are of the utmost importance or whether there it's even less guarantee than their properly disposals.

SD: yeah when I really think I learned and maybe you know an answer is that in Germany for example we have the legislation for electronic waste that the manufacturers supposed to take it back but then looking at Germany for example I mean like 80% is imported from from Asia and then in Germany itself they're like 3 manufacturers with little capacity and then I've been talking to like a European manufacturer he was saying that by policy/legislation it is fixed that manufacturers are supposed to deal with the end of life and recycling and I mean there are issues with recycling but this is another topic. He was saying due to the capacity manufacturers have and the installation-grow that is supposed to happen within the next years it's basically impossible to deal with the end of life management from the manufacturers. So, the legislation basically has a flaw. Is this something you also did like touch in your research in anyways or is this may be too far off.

E3: I'm not sure that I understand why there is a flaw in that respect

SD: Because he was saying that it's basically not possible so it will not be happening and then the manufacturers do. Because they are only three in Germany and then if all three needed to take order as they issue right now is that like Germany wants to be less dependent from for example other countries showing the current situation and the necessity of it. Then they will grow their manufacturing rates and this is what they will be dealing with and then as soon as we're going to hit the waste issue that is going to come with PV which they're supposed to take back and recycle they will not be responsible for dealing with this because and then it's going to be a problem left alone somehow. Did I make myself clear?

E3: yeah I still don't fully understand why they were they considered that an issue because if you to reach the scale that you are able to produce this amounts of panels then this scale of operation should also allow you to deal with the with the waste. The problem currently is that you're actually dealing with waste. What I mean is that recycling these things is actually quite hard, it is far from cost effective. So there are a lot of things that need to be done with respect to the design of these panels to make it easier to do something with them afterwards or at least regained the materials. This one of their of their main issues. I'm not sure that whether the company reaches their scale should be an issue. Unless they become responsible for also sort of external foreign panels but I don't think that that is the case.

SD: He was more picturing it as like that it was good for them to get out of the responsibility in that sense that they would not be needing to dealing with it and then it's like that how the policy because I mean the manufacturer basically only cares about like minimising prices in their production and then selling as cost efficient as possible and then obviously like dealing with recycling and the cost with it is nothing they would want to but in general it's really like it super needed for like having a truly sustainable energy system. This is the design flaw of the legislation I was referring to that then in the end the manufacturer will not be dealing with it.

E3: That is true but there are several initiatives in several sectors actually which is good extended producer responsibility where this is really tackled that as a producer you have the responsibility to deal with whatever you put on the market in the end. So there is some legislation starting to pop up on this topic and so that would that would help and then all of a sudden there will be obliged to think about how to do this and to make sure that these panels are that you can at least recycle them this is currently they I mean there is no incentive at all to make them in anyway recyclable because it's somebody else's responsibility and it's probably cheaper to do not make them recyclable and once you install this kind of policy they will have an incentive to do so

SD: Yeah especially because I mean like what I know from the legislation is that only like 80% of the weight needs to be recovered and then it's usually that glass and aluminium which nobody really does care too much about not that I'm saying it's not important but I mean the really scarce materials are not really recovered which is super sad. Maybe just because I'm trying to put it in perspective for myself. When I started this topic I really imagine that like especially in renewable energies it would be much more about the incentive of yeah like fighting climate change and turning the word for a better place but what I'm learning now especially when I look at the stages individually that everyone is looking for themselves. I mean it's always a trade off. I mean its performance in progress. You need to balance out between your financial performance and then on the other side your sdg-based side. an but I mean maybe it's because you've worked in this like in this field maybe you can tell me your experience with it is my perspective right or do you think it's more of a pessimistic perspective on the renewable energy sector?

E3: You're asking that to an old guy I should not spoil the youth with pessimistic perspectives should I I mean it's realistically properly like I yeah I I think it's it's actually pretty simple a company is a an Organism that has the purpose to make money and that's what it will do if you do not put necessary constraints there for it to make money in a proper way the mechanism is such that it will just create money and follow the rules that are there but if you don't make these rules right companies will not I mean there they are in competition so if your competitor is able to do things cheaper considerably cheaper than you will be not maybe not necessarily going out of business but you will remain smaller because yeah you can you can probably attract like 10 maybe 15% of the market of people who are just choosing you consciously because you're doing the right thing but 85 to 90% of the people will maybe not even have the luxury to go for the more expensive but right choice they may just have to they may not have the money to do this choice so that's why I believe that things like policy and an making sure the proper technologies are there are really I mean counting on the companies are people which will be doing the right thing no that will not work in the end but that's not necessarily a pessimistic view is just as you say realistic here but that's why we have to install for the policy and make sure that technologies are there to do the things we want to do I mean you can you can install policy for the blades of windmills that are notoriously hard to recycle yeah so that's where technology is currently lacking. Or you can make it obligatory to recycle them but if there's no technology it doesn't mean anything so that's why I think projects like ours but also numerous others yeah can help you make these steps and come up with ideas like how should we do it, what kind of rules do we need. Because it's a difficult game in installing the right rules necessary rules also not too many but you don't want to yeah you don't want to end up in an economy where you are going to direct all the companies that's not the intention is to just some constraints so I did I think that's where yeah where project like ours but those other projects can really contribute a lot by giving insight into what works and what doesn't.

SD: yeah that was actually one of my question about but you already kind of answered it. I wanted to know what is most important and you already said policy is the only solution. Adding to that what about collaboration? Because this is something I've also been thinking about like if it just would be the same person doing everything then it would make so much more sentence the way that like the incentive is bigger but then again it's the issue of somebody monopolising the market or something but yeah

E3: But that's where things like this extended producer responsibility or this product service model that we propose that's yeah that's actually the same kind of reasoning. Keeping responsibility, not sort of spreading it out over the value chain and in the end putting it in the hands of the end customer. The end-consumer doesn't really have the proper means of doing the right thing. Even if she or he wants to. So that's actually indeed that proper cooperation yeah I think cooperation and in any circular economy. Circular economy is actually a quite complex thing. Because yeah it's all very nice to say okay you should recycle but that means that there should be at demand for whatever materials come out of it. So you need proper links to probably other value chains. The simplest idea way of circular economy is that the glass from these panels would just end up in new panels because you need glass yeah that's actually a bit a simple view that hardly ever hardly ever works that way. So that means that whatever comes out of your value chain in the end after the end of life there should be demand for that and that's what you refer to it with cooperation if you know beforehand what other companies are looking for you may be able to sort of change whatever you do before that such that at the end of the pipe this thing comes out. But I mean that starts really at the beginning.

SD: Yeah I mean we're not there yet I mean this materials are about to be scarce but this is something that is also not happening yet so I mean and they will always be other technologies around it. Thank you so much already but one question the extended producer responsibility is also basically like any legislation principle like a policy?

E3: You will see that in big number of sectors popping up that producers will become more responsible for whatever they put on the market they cannot just put it on the market and then forget about it. They will have some responsibility of making sure that whatever yeah it ends up at has to be treated in the right way

SD: nice okay perfect thank you so much I think actually like this word is already great insight to me like is a super nice overview. I will stop the recording.