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Does the Rubber Meet the Road? Assessing the Potential of Devulcanization Technologies for the Innovation of Tire Rubber Recycling

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Abstract: Innovation is crucial to meet the circular economy goals for tire recycling. Devulcanization, an innovative recycling method of reprocessing tire rubber, offers a pathway towards achieving circular economy objectives. While previous research on devulcanization has primarily focused on technical aspects, this study shifts the focus towards identifying opportunities and barriers for innovation through devulcanization. This research utilizes the Technological Innovation System framework as a basis to analyze the dynamics of innovation within value chains and innovation networks. Across Europe, 36 organizations were identified that develop and utilize devulcanization to transform rubber from end-of-life tires into a valuable resource for new rubber products. In this study, a semi-structured in-depth interview approach was applied to interview 12 organizations that have developed or utilize technologies for the devulcanization of tire rubber. It was found that the development of various devulcanization approaches for diverse types of products has created opportunities for upscaling. To capitalize on these opportunities, organizations need to collaborate throughout the entire value chain of tire production and recycling. Achieving this collaboration requires interventions across the industry.

Keywords: circular economy; recycling; devulcanization; technological innovation systems (TIS); tires; rubber

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1. Introduction

The European Union aims to realize a circular economy by 2050 for all products and materials [1], but the transition to a circular economy is still at an early stage [2,3]. In a circular economy, industries, consumers and other stakeholders minimize their use of virgin raw materials and non-renewable energy. The value of products, components and materials is preserved over time in a regenerative system by various economic activities, such as reusing, remanufacturing or recycling [4]. However, tire rubber recycling is challenging due to the vulcanization process, which cross-links rubber to a three-dimensional network, making it difficult to recycle without losing essential properties [5]. More than 58% of all rubber is consumed for passenger car and truck tires [6], which makes tire rubber a key topic for the circular economy.

Currently, the value of passenger and truck car tires is hardly preserved when tires have reached their end-of-life stages. In Europe, tire collectors gathered over 3.5 million tons of end-of-life tires in 2019 [7], which is the equivalent of over 300 million tires. Although the majority of these end-of-life tires are collected, most of the rubber from end-of-life tires is incinerated or downcycled and used for low-value applications, such as artificial turf on playgrounds or floor mats [8,9]. The shift to a circular economy requires rubber from end-of-life tires to become a valuable resource [8].

Devulcanization is a promising route to rubber recycling, encompassing a set of technologies aimed at specifically breaking the sulfur cross-links in vulcanized rubber while inflicting minimal damage to carbon-based molecular rubber polymer chains [10]. This enables the vulcanization process of rubber to be reversed, making the material suitable to add to rubber compounds in the production of new products [11,12]. For this reason, devulcanization is considered to be a key technology to enable the shift towards a circular economy for tires [13,14].

Devulcanization has not yet achieved industrial-scale implementation, but this can change when market conditions shift their focus towards the circular economy. In 2004, a global evaluation was conducted on the utilization of devulcanization technology for tire recycling. Devulcanization appeared to exist only for research and development purposes at a scale of no more than 45 kg/h. At that time, researchers stated that "devulcanization faces an uphill struggle to be competitive with virgin rubber" [15]. The observed barriers were a lack of reliable data on devulcanization, no clear standards, and short-term, price-driven markets [15]. Since then, however, devulcanization has continued to develop and is now increasingly being applied by companies worldwide [16].

Although many technical innovations took place to push devulcanization [14], a transition to a circular economy also requires systemic innovations. These are comprehensive innovation processes that change how products and materials flow through value chains during their lifespan [17]. However, the main body of academic literature on devulcanization primarily focuses on the technical aspects [5,14,16,18]. Value chains are, however, crucial because industrial devulcanization involves a process that includes a variety of process steps like sorting tires, separating tire rubber into granulate or powder, conducting the devulcanization process, and applying devulcanized material in new products [19]. The development of such value chains is an innovation process [20] in which organizations face various opportunities and barriers [21]. A knowledge gap seems to exist concerning the application of industrial devulcanization technology to innovate tire recycling in value chains. This research therefore aims to address this knowledge gap by investigating the following question: *what barriers and opportunities have emerged within innovation networks for the development of industrial devulcanization processes in Europe?* To assess the implementation potential of devulcanization technologies, interviews were conducted with actors along the value chain. These interviews were analyzed using a Technological Innovation System (TIS) framework.

This article is structured as follows: The Background Section introduces devulcanization technologies and industrial tire devulcanization activities. This section also describes the TIS framework, which is used to investigate innovation processes related to devulcanization. The Methods Section describes the interview setup, coding and analysis. The Results Section reports on the main findings from the interviews, aligned with activities in the value chain and the key innovation processes in the TIS framework. The Discussion Section interprets the results and identifies the main barriers and opportunities for developing industrial devulcanization processes in Europe. This analysis includes aspects such as entrepreneurial activities, market formation and resource mobilization. The Discussion and Conclusion sections present the main insight and their implications for tire recycling through devulcanization in Europe.

2. Background

2.1. Devulcanization

Vulcanization is a vital step in tire production. Tires consist of various rubber compounds reinforced with steel and canvas and contain various filler materials [22] (Figure 1). Rubbers are mixed with a variety of additives to create compounds tailored to the functions of the various parts of the tire. These compounds are joined together using a vulcanization process. The rubber is cured at high temperatures with a vulcanization agent (often sulfur), forming cross-links between the rubber polymer chains. This process bonds the various parts together, but also creates cross-links in the rubber compounds themselves, resulting in strong and elastic three-dimensional molecular structures that cannot be reversed by a simple melting process [23]. Due to the formation of these cross-links, advanced recycling technologies are needed to make rubber suitable for reuse in high-value applications [14].

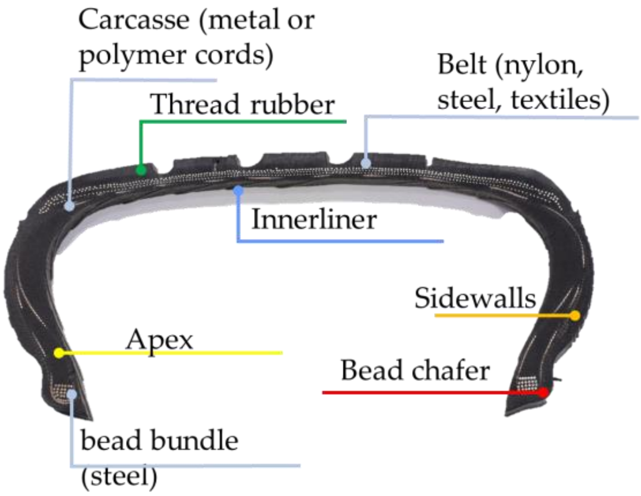

Figure 1. The cross section of a tire highlighting the main components.

Devulcanization is an advanced recycling technology, which means that the sulfur bonds in vulcanized rubber are selectively broken, minimizing random polymer scission whenever possible, as shown in Figure 2 [12]. Although the devulcanization of tire rubber was already applied on a laboratory scale at least 95 years ago [24], recent decades have paved the way for devulcanization as a suitable technology for tire recycling [14]. The continuous development of devulcanization is evident from the rise in scientific papers, increasing from 10 papers in 2000 to 147 papers in 2021. In the same period, over 300 patents were filed, indicating the relevance of this technology for the tire and recycling industries [16].

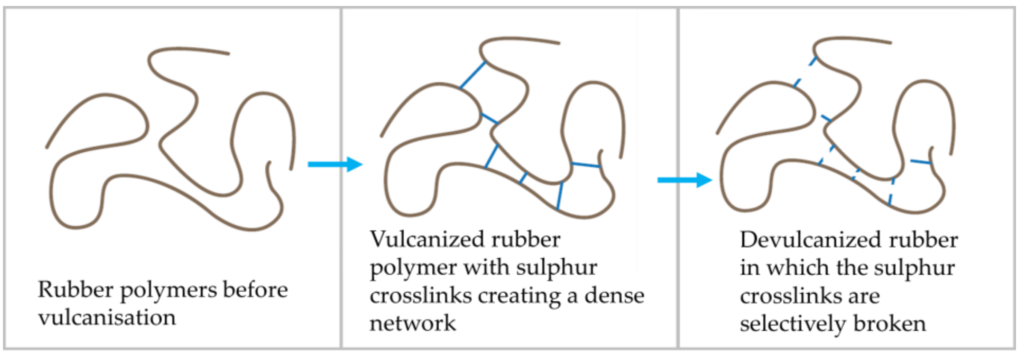

Figure 2. Concept of vulcanization and devulcanization of rubber.

The properties of a devulcanized material are not solely dependent on the devulcanization technique but also on the characteristics of the end-of-life rubber being devulcanized [25]. The properties of the initial end-of-life tire rubber are strongly influenced by the combination of rubbers used, the quantities and types of fillers employed, and the chemicals utilized for vulcanization. If tire producers add new types of fillers or additives to rubber, this could have a significant effect on devulcanization. For instance, incorporating silica into tire rubber requires modifications to the devulcanization process to achieve the most optimal properties of the devulcanized material [26]. This implies that the quality of devulcanization is also highly dependent on the input material.

The devulcanization of tire rubber can best be described as a process in which various industrial activities are combined and optimized [13,14]. In the material journey for this process [16,19,26,27], the following factors regarding the quality and scale of devulcanization activities can be identified:

Collecting tires: Each EU member state has its own management system for the collection and treatment of end-of-life tires. The scope and implementation of these management systems differ per country [16]. This implies that devulcanizing companies based in different European countries receive varying supplies of tire rubber.

Separating tire rubber: When tires reach the end-of-life phase, they typically undergo recycling processes, during which they are shredded, and the rubber is separated from the metal and canvas. The remaining rubber is grinded to rubber crumb or powder in various sizes [28]. In some cases, more homogeneous rubber can be made available for devulcanization. For example, in the process of retreading tires, only the worn-out treads are replaced, and not the entire tires [27]. This taken-off tread rubber provides another, more homogeneous source of tire rubber. The processing of selected tires or sorted granulate or powder leads to a more consistent quality of devulcanized material [12,19,26].

Devulcanizing tire rubber: The main devulcanization methods can be categorized into physical, chemical and biological devulcanization. Physical methods include the introduction of heat or kinetic energy. Thermo-mechanical devulcanization is achieved by applying shear forces to heated rubber [18]. Other physical approaches are microwave and ultrasonic irradiation treatments. In a microwave treatment, the temperature of the rubber is increased by radiation [29]. Ultrasonic treatments make use of 'acoustic cavitation' to devulcanize rubber. In this process, microscopic bubbles in the material increase and collapse, separating sulfur bonds in the rubber [18]. Chemical methods involve adding reactive agents to swell the rubber prior to or during a thermo-mechanical process, sometimes in combination with an antioxidant [11,18,26,30].

Adding devulcanized material to compounds: Devulcanization is conducted in conjunction with compounding and re-vulcanization. After devulcanization, the devulcanized material is compounded with rubbers in virgin form and additives, such as accelerators, for re-vulcanization [10,31,32]. Then, the rubber compound is re-vulcanized in a curing process to create rubber products [31].

Developing new products with recycled content: Commercial access to markets is not just dependent on the recycled material itself but also on the capabilities to apply this material [33]. Therefore, it is important for companies to collaborate with manufacturers, the buyers of the material, during their research and development process to ensure that the end product meets their specific needs [34]. This implies that the development of devulcanized material should ultimately lead to a convincing customer proposition that encourages customers to incorporate this material into new products.

Since devulcanization can be understood as a process that combines multiple activities, innovation encompasses more than just technology development. The next section therefore describes the Technological Innovation System framework, which will be used to analyze innovation in a complex environment.

2.2. Technological Innovation Systems

To investigate the devulcanization innovation ecosystem, the Technological Innovation System (TIS) framework is applied as a multi-level research framework that focuses on the networks needed for a technology to emerge and be sustained [35]. The framework is applied in this study to uncover the opportunities and barriers that emerge in these innovation processes. It focuses on the specific knowledge and competences that are either shared or contested amongst actors within the network for the development and use of new technology [36–38].

As tire devulcanization involves a complex technological set of industrial activities, an actor-oriented approach is applied to capture the dynamics within the TIS framework. An actor-oriented approach is a bottom-up approach focusing on the interactional processes from the orientation of actors. These actors are directly engaged with the technology, and the approach describes their interfaces with other actors, technologies and institutions [39,40]. As such, the actor-oriented approach can include the entrepreneur's perspective [41]. In this study, this approach aims to reveal how the TIS framework relates to strategic and operational opportunities and the challenges actors face in the supply chain.

Seven system functions were identified in the innovation process in which the involved actors interact with technology, institutions and wider networks [36,37,42,43]. These system functions are described and related to the devulcanization of rubber in Table 1. Figure 3 combines the main factors of specific interest mentioned for the devulcanization value chain into a single overview.

Table 1. Description of TIS system functions.

System Function	Description of System Function	Related to Devulcanization Value Chain
Entrepreneurial activities	Entrepreneurs and other actors have the ability to bring early technology developments to the market with an initial business idea and then start experimenting to create new opportunities in markets.	Utilization of devulcanization technologies, development of business model, organization of the value chain
Knowledge development	Actors derive knowledge about technology, its conditions, and opportunities and applications from academic research to a more practical learning-by-doing process.	Knowledge generation regarding devulcanization from scientific research and other sources of information; utilization of intellectual property rights
Knowledge diffusion through networks	Actors gather and share information while engaging with other actors in value chains and in other settings.	Knowledge sharing through collaboration and participation in networks and projects
Guidance of the search	Actors seek approaches to address various strategic and practical problems. They are guided by factors such as governmental policies, specific industry standards and technical bottlenecks.	Identified barriers and barriers in the environment
Market formation	Actors introduce new technology into existing markets with established relationships, which may either facilitate or hinder the adoption of this technology.	Uptake of devulcanized material by customers (direct business to business sales), requirements that are set by these customers
Resource mobilization	Actors require financial resources and other types of resources to introduce the new technology, including a company's facilities and human capital.	Sources of funding, capabilities in business model
Acceptance and creation of legitimacy	When actors introduce a new technology, it can be immediately accepted by the industry, but it can also challenge the status quo, leading to opposition that the actors must face.	Purchase of devulcanized material by their customers and, more generally, the uptake of recycled material in their markets

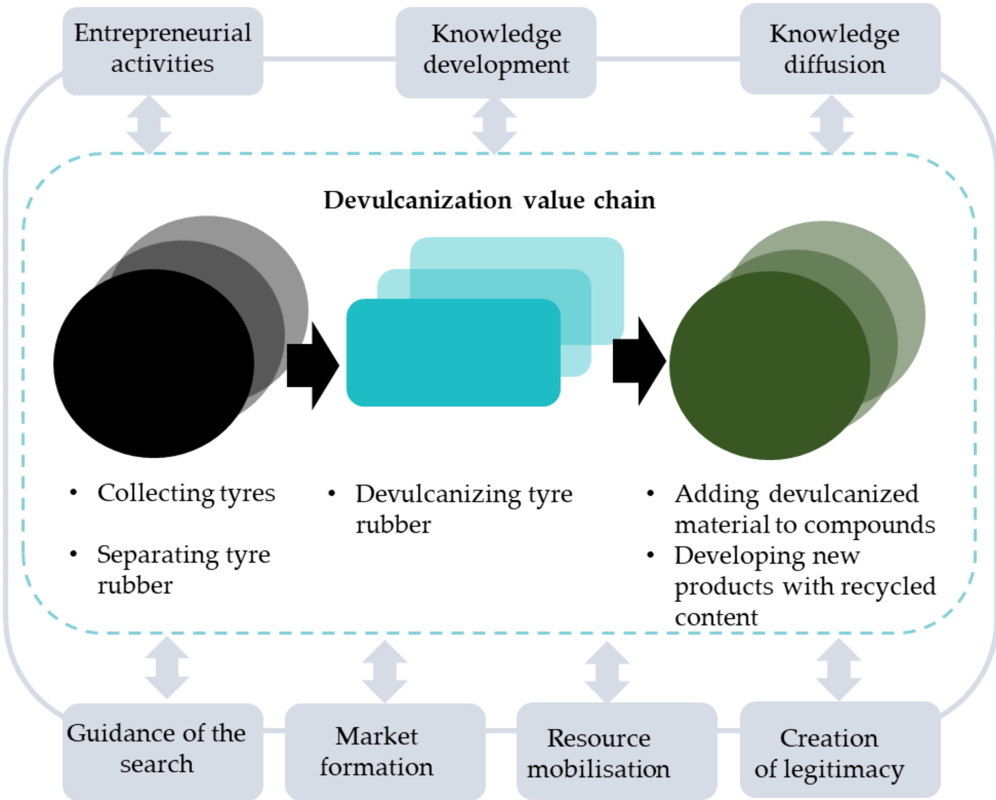

Figure 3. Schematic relationship between system functions and the value chain.

3. Methods

To study the implementation of devulcanization technology in EU tire recycling, organizations were interviewed that contributed to the development and utilization of devulcanization (Section 3.1). The interviews followed a semi-structured approach, as described in Section 3.2. The responses were coded and analyzed using the Technological Innovation System framework described in Section 3.3.

3.1. Participant Selection

Participants were selected using purposive sampling, a method in which organizations were intentionally chosen, rather than randomly selected, to obtain an in-depth understanding of the research topic [44]. In this study, the first step was to identify all actors operating from Europe with experience in devulcanization. Subsequently, a sample of participants was selected from the identified actors. The organizations were selected to encompass various devulcanization technologies, different value chains, and a range of activities within those value chains. They were identified from devulcanization value chains by contacting researchers and entrepreneurs in the field of devulcanization and tracing companies with Google searches. The following search terms were used: devulcanization in combination with the name of a European country. A total of 36 actors contributing to the devulcanization of tire rubber were identified in Europe.

The 36 identified actors were organizations from 12 different countries. Most identified organizations were based in Italy (6), the Netherlands (5) and Spain (4). The remaining 21 organizations were based across Europe. Table 2 provides an overview of the different types of organizations.

Out of the 36 organizations, 12 representatives were interviewed. The interviews lasted about an hour on average. Table 3 provides an overview of the key characteristics of the organizations of the respondents. Of the respondents, 8 were directors, 3 were research and development managers in their organizations or networks, and 1 respondent held a technology and sustainability-related staff position. The 12 interviewed organizations all had industry partners and were participating in joint industry projects, and the information they shared gave broader insights into their own activities. The interviews were conducted in the year 2023 over a period of 10 months. The interviews were carried out until further interviews no longer offered any new insights but instead echoed what was already found in earlier interviews. This stage, referred to as reaching the saturation point in purposive sampling, marked the end of the data collection process [45].

Table 2. Organizations identified per type.

Tire manufacturers	5
Commercial research organizations	5
Suppliers of machines and equipment	6
Suppliers of chemicals	3
Recyclers	17
Total	**36**

Table 3. Main characteristics of companies in sample.

#	Description of Key Activities Related to Devulcanization	Types of Tire Material Collected	Capacity	Type of Process	Applications for Devulcanization
1.	Recycling rubber and developing technology and equipment; IP development for own use	Passenger car and truck tires	R&D-scale	Milling process (use of kinetic energy)	Asphalt
2	Devulcanizing rubber and licensing IP to other companies	Passenger car and truck tires	2 ton/h	Thermo-mechanical process with chemicals	General rubber goods and truck tires
3	Sorting and separating tire rubber; devulcanized tire rubber in the past, now consultancy for other companies	Passenger car and truck tires	2 ton/h, when it comes on stream	Thermo-mechanical process	General rubber goods and truck tires
4	Sorting and separating tire rubber and devulcanizing tire rubber	Passenger car, truck and bicycle tires and inner liners	1.5 ton/h	Thermo-mechanical process with chemicals	General rubber goods
5	Supplying devulcanization equipment; owns a production line for separating tire rubber and devulcanization for R&D	Passenger car tires	R&D-scale	Thermo-mechanical process with chemicals	General rubber goods
6	Sorting and separating tire rubber and devulcanizing tire rubber	Passenger car tires	0.75 ton/h	Thermo-mechanical process with chemicals	Asphalt and general rubber goods
7	Setting up a logistical system for tire collection and testing devulcanization equipment with a partner	Off the road and airplane tires	Startup	Thermo-mechanical process	General rubber goods
8	Devulcanizing rubber, developing devulcanization method and devulcanization aids (chemicals); aims to license IP to other companies in the near future	Passenger car and truck tires (whole tires and treads)	1.5 ton/h	Thermo-mechanical process with chemicals	General rubber goods
9	Researching rubber devulcanization in collaboration with companies (knowledge institute)	Passenger car and truck tires	Laboratory scale and at site of clients	Thermo-mechanical process with chemicals	General rubber goods
10	Devulcanizing various types of tire rubber	Truck tire treads and inner liners	+/− 2.5 ton/h	Thermo-mechanical process	Truck tires and general rubber goods

Table 3. *Cont.*

#	Description of Key Activities Related to Devulcanization	Types of Tire Material Collected	Capacity	Type of Process	Applications for Devulcanization
11	Researching devulcanization with companies; owns a line for devulcanization for R&D purposes and has just completed a project on tire devulcanization (knowledge institute)	Passenger car and truck tires	0.03 ton/h	Microwave	General rubber goods
12	Researching and developing the application of devulcanized rubber in rubber compounds of new tires (tire producer)	Truck tires (whole tires and treads)	Research at lab-scale	Receives material from thermo-mechanical process with chemicals	Truck tires

3.2. Semi-Structured Interviews

Qualitative data were collected by means of in-depth interviews, which were semi-structured using a set of questions as a topic guide during the interview [45]. Such in-depth interviews were conducted because this allowed the respondents to bring forward complex and sensitive issues [46]. Furthermore, this approach allowed the interviewer to maintain a clear focus on the topic of devulcanization while allowing respondents to bring up topics they felt were related to the topic [47]. The semi-structured interview method provides contextual information with questions tailored to the specific background and position of respondents. This method provides an avenue to discuss opportunities, barriers, potential solutions and strategies for overcoming these barriers, which can offer key insights in innovation systems.

The interviews were either conducted in person or via video conferencing. Before the interviews, the respondents received information about the subject, the interview approach, and how the data would be stored and analyzed by the researcher, which is presented in the interview guide in Appendix A. No information is presented that could be traced back to a particular person or organization.

In the interview questions, the company representatives were not guided towards the TIS framework to avoid a bias, but the respondents were interviewed about their perceptions and experiences related to devulcanization in the value chain and the circular economy. For each category, more specific topics and questions were developed. The topic list (formulated as a set of questions) can be found in Appendix B. The interviews were recorded and then transcribed. The manuscripts were then coded with software for analyzing qualitative data.

3.3. Interview Analysis

After the interviews were conducted and transcribed, the answers were structured by a set of codes that matched the key activities in the value chain and the system function of the TIS framework. For the system function of knowledge development, additional information was acquired by utilizing Google Patent Search to gather more insights about patents related to devulcanization.

The codes for the value chain were aligned with the topics described in Section 2 and shown in Figure 3. The additional codes were in line with the 'system functions' from the TIS framework. Appendix C provides an overview of the codes used, matching the classification as described in Section 2.2.

4. Results

The first section presents the key industrial activities within the devulcanization value chain. The second section provides an overview of the identified barriers and opportunities for all system functions within the Technological Innovation System (TIS) framework pertaining to the development of industrial devulcanization processes in Europe.

4.1. Key Industrial Activities in the Value Chain

Collecting tires. All interviewed companies organized their supply chains to ensure a steady supply of tire rubber with the goal of providing devulcanized material with a consistent quality. Four companies made arrangements with their tire rubber suppliers to meet specific quality standards, while another four companies conducted their own processes of sorting and separating tires. Additionally, two companies separated truck and passenger car tires, one company focused on removing tires older than 10 years, and one company also separated summer and winter/all-season tires. Thus, pre-sorting was managed both through supplier agreements and in-house processing, and each company employed its own set of selection criteria.

Separating tires. Most companies that devulcanize tires used the granulate of whole tires, but in some cases, the tire rubber was first separated. Three companies purchase tread rubber from retreading companies, obtaining rubber with more uniform specifications. Additionally, a developer of devulcanization equipment introduced a new technology to scrape the treads of passenger car tires, thereby obtaining pure tread tire rubber. Devulcanizing only the tread rubber resulted in a higher quality of devulcanized material compared to rubber from whole tires.

Devulcanizing tire rubber. Although some recycling companies were in the process of upscaling, the largest facility had a capacity of 2.5 ton/h. For reference, in 2018, 3.26 million tons of tire rubber were collected in Europe [7], which would roughly necessitate a total capacity of 410 tons per hour. This highlights that devulcanization continues to occupy a niche within the recycling industry.

While the majority of companies applied thermo-mechanical processes, sometimes supported by chemical devulcanization aids, the interviews also unveiled significant differences between these companies. In addition to variations in the supply of sorted and separated tire rubber, distinctions were noted in terms of the temperature employed, the use of specific chemicals or solvents, the size of the powder or granulate, and the equipment used (with extruders and autoclaves being the most common). Notably, one company employed three different devulcanization methods in a single facility to optimize processes for three distinct sources of recovered tire rubber. There were large variations in feedstock and equipment. Four respondents claimed that their technology was more sustainable than similar devulcanization technologies, citing different arguments such as the absence of chemicals, the use of non-hazardous chemicals, fully optimized equipment or a process conducted at lower temperatures. It can therefore be concluded that the diverse approaches taken in devulcanization processing activities highlight companies' strategic customizations of these methods to align with their specific business objectives and sustainability targets.

Adding devulcanized material to compounds. The respondents mentioned that their devulcanized material was mostly compounded with rubber from primary sources to meet the specifications needed for new products. The ratio depended on the application and customer demands, but generally, 10 to 20 percent of devulcanized rubber was added to a compound. This compounding was mostly managed by tire or rubber goods manufacturers, sometimes in collaboration with recyclers. When devulcanized material was added to a rubber compound, the impact of the devulcanized material on the properties of the new compound needed to be studied.

Developing new products with recycled content. In the interviews, the respondents mentioned various applications and markets for devulcanized rubber on an industrial scale as follows:

- Using devulcanized rubber as a material for certain components of tires: Two respondents suggested that devulcanized material could be blended into rubber compounds for the less safety-critical parts of new tires.
- Using devulcanized rubber as a material for 'general rubber goods': This term refers to a wide range of markets and product demands, including conveyor belts and molded products for automotive parts.

- Using devulcanized rubber as a modifier in asphalt: Two respondents developed devulcanized material as a replacement or addition to SBS (styrene–butadiene–styrene), which is used as a modifier in asphalt to enhance abrasion resistance as well as resistance to high temperatures. Devulcanized rubber exhibited better results in asphalt than granulated rubber alone.

These responses suggest that devulcanized rubber can be applied in a range of applications. However, it is not applied in the most critical applications.

4.2. Technological Innovation System Functions

Entrepreneurial activities. An opportunity for the development of industrial devulcanization processes lies in the creation of new business models that support these processes. For six of the interviewed companies, devulcanization was at the core of their business model, while others also engaged in other activities, such as the development of different technologies. Their business model was not entirely dependent on the devulcanization of tires. Among the companies reliant on devulcanization activities, four were part of a larger holding company, and the other two were startups that collaborated with other companies to organize a value chain and establish their business cases. Thus, the interviewed companies not only had different devulcanization processes but also possessed distinct business models, both in terms of activities and organizational structure.

A barrier existed for the development of industrial devulcanization processes because the quality of devulcanized material depended not only on the devulcanization process but also on other activities within the value chain. The respondents generated new knowledge on improving and scaling up industrial processes, integrating activities in the supply chain, and facilitating customers' use of devulcanized material in new compounds. Five companies actively participated in the compounding process led by tire and rubber goods manufacturers by providing advice and conducting additional tests. In summary, a barrier exists in the need for aligning activities throughout the value chain, requiring collaborative efforts and engagements from tire and rubber goods manufacturers.

Knowledge development. An opportunity arose from the development of a significant number of novel devulcanization technologies, ranging from research and development facilities to industrial processes. All respondents worked with patented devulcanization technologies. While tire manufacturers globally held the majority of intellectual property (IP), these companies primarily relied on IP from other sources. In four cases, the devulcanization method was developed by universities that made their IP available through licensing to companies. Three companies developed their own devulcanization methods and filed for IP rights. One company developed an entirely new devulcanization method within an EU-funded project. Another company, initially not focused on devulcanizing rubber, coincidentally discovered a novel approach while experimenting with another recycling method. This diversity in the origin of intellectual property from these companies illustrates a range of innovation pathways.

The variation in devulcanization processes and the diverse sources of end-of-life tire rubber also posed a barrier because it made it challenging for manufacturers to compare the composition and quality of devulcanized rubber from different suppliers. Eight of the companies initiated their devulcanization activities within the past seven years, introducing new types of devulcanized material to the market. Each company branded its own devulcanized material and defined its own grades. The respondents noted incidents where manufacturers were unwilling to test their material because other companies had already presented a similar type of material. A tire manufacturer pointed out that it had conducted research and development on the devulcanized material of just one supplier due to the necessary research and development efforts. Thus, although many innovations occurred, this did not automatically result in a greater adoption of the technology.

Knowledge diffusion. An opportunity existed in the collaboration of various knowledge institutes, recycling companies, and suppliers of equipment and chemicals to develop industrial devulcanization processes within projects. Seven respondents had recently participated in projects to (further) develop devulcanization, funded either by the EU or national governments. These projects were mainly used to (further) develop their devulcanization technologies. The interviews revealed that the participating organizations played various roles in technology development and information sharing within these projects, including the following key roles for technology development:

- Developers of the chemical process of devulcanization, primarily knowledge institutions, including universities and commercial knowledge institutes and, occasionally, suppliers of chemical devulcanization aids.
- Developers of machinery and other equipment who developed an industrial devulcanization process that allowed devulcanization to be scaled up to an industrial level.
- Tire and rubber goods manufacturers who led investigations into the extent to which devulcanized rubber compounds could replace virgin rubber and additives in new compounds for their applications.

A barrier was that the diffusion of knowledge often remained confined to those projects and their associated value chains. The willingness of companies to license intellectual property and share knowledge reflected a potential avenue for overcoming this obstacle for knowledge diffusion and commercial selling.

Guidance of the search. An opportunity arose as governments funded projects to stimulate the development of devulcanization. For the adoption of devulcanization, customers of devulcanized rubber had to engage in research and development activities to add devulcanized material to their compounds. In most projects, one or more launching customers participated in testing devulcanized material for their applications. These projects, with various types of organizations, led to a rapid development of new technologies and applications.

A barrier was identified because most tire and rubber goods manufacturers did not have the incentive to replace virgin rubber with devulcanized material in their products, and there was a lack of stimulating regulations. In the current situation, potential customers were mostly interested in devulcanized rubber to meet certain sustainability goals. Three respondents mentioned that there were no rules and regulations at the national or European level that stimulated manufacturers to use recycled rubber instead of virgin rubber. Two respondents advocated for national or European regulations that would require manufacturers to incorporate a percentage of recycled content into their compounds. This indicates that the existing rules and regulations do not stimulate the uptake of recycled materials, such as devulcanized rubber.

Market formation. An opportunity arose as the attention from tire manufacturers and other rubber product manufacturers increased, according to the respondents. Three respondents experienced a rise in the number of companies showing interest in purchasing devulcanized rubber in the past year. Three respondents had already supplied devulcanized material to tire manufacturers. One of these companies had already supplied rubber in large quantities, while the other companies were undergoing a preparation process to meet the demands set by manufacturers. Although the interest in devulcanized material was increasing, this did not always directly translate into higher sales.

A barrier existed as there was no established market for devulcanized rubber. Assessing devulcanized material by tire and rubber goods manufacturers was challenging due to its different properties compared to virgin rubber. Five respondents indicated that many rubber goods manufacturers were not yet inclined to use any recycled rubber. Four recycling companies stated that price negotiation for devulcanized material with rubber goods manufacturers was often difficult. As this was a new type of material, there was not yet a clear reference price. The interviewed tire manufacturer stated that the price their purchasing department was willing to pay for devulcanized material was significantly lower than the price for virgin rubber. One recycler stated that his company was forced to stop its operations because the market value of virgin rubber suddenly declined, and customers also demanded lower prices for the devulcanized material. Therefore, market development was complicated by the unfamiliarity with the material characteristics of devulcanized material on the one hand, and the volatility and often low prices of virgin rubber on the other hand.

Resource Mobilization. An opportunity presented itself when companies had access to multiple sources of income for the development of technology. The financial resources identified for the development of industrial devulcanization processes came from government funds and corporate and private investments. Most innovations in the technology were developed in subsidized projects.

For better market expansion, most companies encountered a barrier in the need for additional customers, specifically tire and rubber goods manufacturers, to scale up their production. In some cases, it took months or even years of research and development before certain customers were willing to incorporate devulcanized material into their compounds. These long lead times made it challenging for companies to generate sufficient income from their sales, primarily because extended research and development trajectories did not guarantee a confirmed market uptake.

Creation of legitimacy. An opportunity emerged as devulcanization gained recognition as a recycling approach in the industry. This was manifested not only by an increase in potential customers showing interest but also by the heightened involvement of other interested parties, such as investors. The respondents also mentioned that they could present their technology at industry conferences.

However, 10 respondents also pointed out that the acceptance of devulcanized material was also a barrier. One respondent from a recycling company mentioned the challenge of explaining the distinctiveness of devulcanized material to customers, investors and interested parties. Another respondent raised a similar issue regarding the use of devulcanized rubber as a plasticizer in asphalt, highlighting that this was a novel material for such an application.

A second barrier was the lack of standardization for devulcanized materials, which hindered a fair comparison between the different types of devulcanized materials provided by recycling companies. Although the respondents mentioned general ISO standards [48,49] and EcoVadis sustainability ratings [50], no testing protocols or procedures were used as standards for the industry to compare the various types of devulcanized materials. Prior research showed that research groups used their own procedures and laboratory standards for devulcanized material, which made it difficult to draw a comparison between various available laboratory studies. Therefore specific standards were recommended [51], which could be derived from industry needs followed by a translation to industry standards. In conclusion, despite there being a growing acknowledgment of devulcanization, the identified barriers underscore the need for continuous efforts to address challenges related to material development and standards that must be widely accepted by the industry.

Table 4 shows an overview of the opportunities and barriers identified for the different TIS system functions. From the more detailed description below, it will become evident that these system functions are interdependent.

Table 4. Key barriers and opportunities for each system function from the TIS framework.

System Function	**Opportunities**	**Barriers**
Entrepreneurial Activities	Technologies and business models tailored to devulcanize different types of tire rubber	Collaboration in the value chain and engagements from tire and rubber goods manufacturers is needed
Knowledge Development	A large number of new devulcanization technologies were developed for devulcanization on an industrial scale	Due to variation in devulcanization technologies and different supplies of end-of-life tire rubber, it is hard to compare the composition and quality of devulcanized rubber

Table 4. *Cont.*

System Function	Opportunities	Barriers
Knowledge Diffusion	Various knowledge institutes, recycling companies and suppliers of equipment and chemicals collaborated with the aim to develop industrial devulcanization methods in projects	Knowledge generated within projects often remains contained within the project boundaries
Guidance of the Search	Governments funded projects to stimulate the development of devulcanization	In the regulatory landscape, most tire and rubber goods producers do not have financial incentives to replace virgin rubber with devulcanized material in their products
Market Formation	The attention paid to devulcanization by tire and rubber goods manufacturers is increasing	No established market exists for upscaling devulcanization on an industrial level; more launching customers are needed, especially ones that not only conduct research and development but also purchase devulcanized material
Resource Mobilization	Companies had access to multiple sources of income for the development of technology from investors as well as subsidies from governments	Tire and rubber goods manufacturers need to perform extensive research and development to incorporate devulcanized rubber in products, a process which incurs significant resources
Acceptance and Creation of Legitimacy	Increased attention for devulcanization within the industry	Assessing devulcanized rubber needs additional efforts due to its different properties compared to virgin rubber; there are no industry-wide definitions, protocols or standards for assessing devulcanized material

5. Discussion

This study identified the main opportunities and barriers for scaling up the industrial devulcanization of tire rubber, aiming to contribute to a circular economy. This was achieved by framing the opportunities and barriers within the context of the devulcanization value chain and relating them to industry system levels through the system functions of the Technological Innovation System (TIS) framework. In this discussion, first, the connections between the opportunities are described and presented in Figure 4, followed by the description of the barriers, depicted in Figure 5.

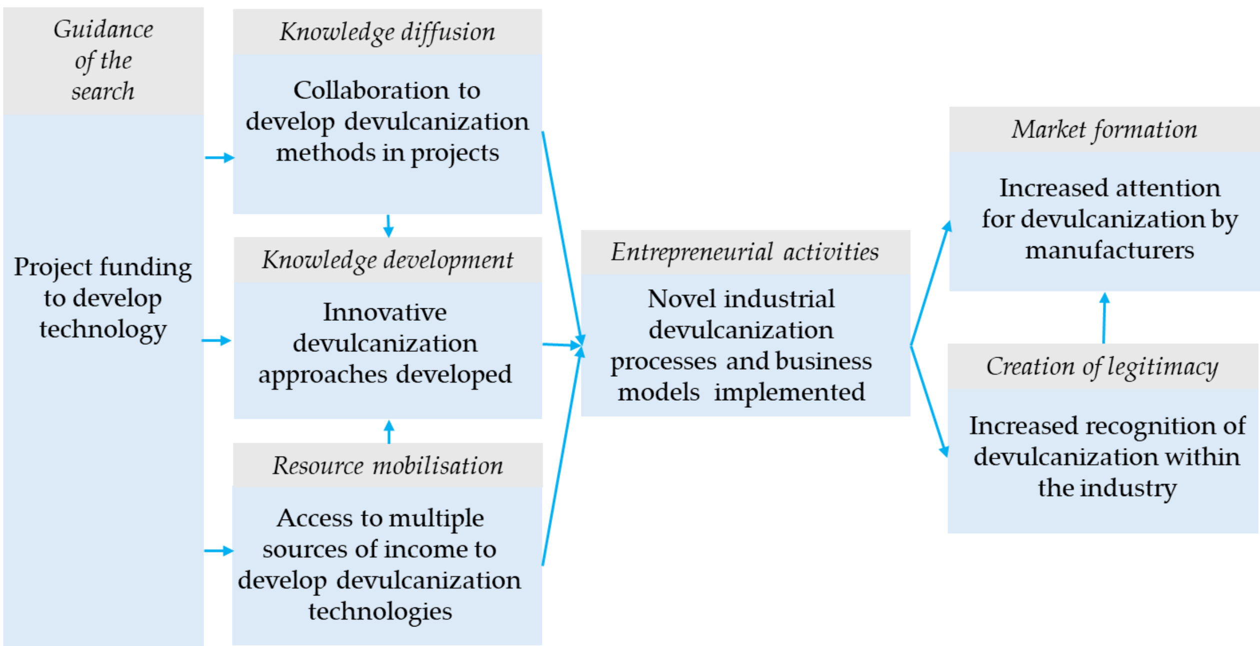

Figure 4. Connections between identified opportunities.

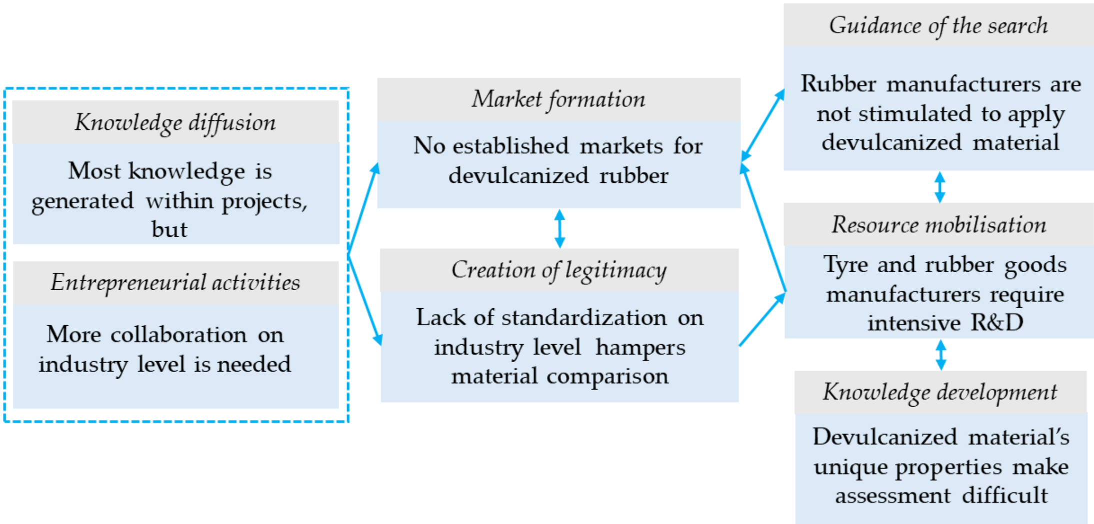

Figure 5. Connections between identified barriers.

The central opportunity for devulcanization mainly pertains to technology and business model development, providing companies with the capabilities to devulcanize tire rubber through various processes. This opportunity arises from numerous collaborations (knowledge diffusion), organizing resources (resource mobilization) and technological innovations (knowledge development), which all aim to develop and scale up devulcanization processes. These collective efforts have led to a significant increase in industrial devulcanization processes across Europe, providing entrepreneurs with the opportunity to develop business models, reach customers and scale up industrial devulcanization processes (entrepreneurial activities). These entrepreneurial activities lead to other opportunities; novel industrial devulcanization processes create greater recognition of the technology's potential (creation of legitimacy) and attract the attention of tire and rubber goods manufacturers (market formation). Thus, most opportunities are connected to entrepreneurial activities as rubber recycling techniques, which are essential for the further development of devulcanization.

Project funding (guidance of the search) was a driving force for many of the developments and is therefore a key opportunity for innovation. However, a limitation of these innovation projects is that they often prioritize technology push over other crucial aspects, such as market research and understanding customer needs, resulting in the absence of market pull.

The identified barriers mainly address key industry-level topics that may hinder the further development of devulcanization and the uptake of devulcanized tire rubber as a raw material by the market and are less related to technology. A central barrier to devulcanization is the absence of established markets for devulcanized rubber (market formation).

There is a lack of demand because manufacturers of tires and general rubber goods currently do not have strong financial incentives to apply devulcanized rubber in new products due to the legislative landscape (guidance of the search). There is also a lower demand because these manufacturers have to invest in intensive research and development processes to add devulcanized rubber to their compounds, which is a time-consuming and often costly process (resource mobilization). Due to differences in mechanical and processing properties of the various types of devulcanized material compared to virgin rubber (knowledge development), devulcanized materials are not only branded differently but also vary due to differences in devulcanization processes and types of tire rubber. The research and development costs of manufacturers are also high due to the absence of industry-wide accepted definitions and standards to measure and categorize the properties and quality of devulcanized material (creation of legitimacy). However, creating industry-wide standards and promoting devulcanized material requires collaboration that surpasses project-based relationships (knowledge diffusion) and should be organized at the industry level (entrepreneurial activities). Thus, to overcome these barriers, a systemic innovation is needed, which is a type of innovation that fosters industry-wide commitment, combines solutions throughout supply chains, and promotes collaboration to increase the utilization of recycled rubber from tires.

In plastic recycling, similar challenges have been addressed through regulations [52–54]. Implementing similar regulations for rubber recycling, such as mandatory recycled content [55] or a tax on the use of virgin rubber [56], could be considered to facilitate the uptake of recycled rubber. However, it is recommended to first study the effects of these regulations, as this topic has not yet been explored in the context of rubber recycling.

In this study, the TIS framework was used to analyze the innovation system from an actor-oriented approach. The advantage of conducting this actor-oriented study first is that it has already identified the challenges of organizations that are immediately involved with devulcanization. However, a limitation of the actor orientation is that innovations are mainly viewed from the perspective of actors in the value chain. Other studies with actor-oriented perspectives also mentioned a more limited scope [40,41]. A recommendation is a follow-up study, which is a complementary, more extensive analysis of the innovation network that also includes other actors, such as policy makers.

The analysis was focused on Europe, which is different from the context of other parts of the world. For example, the devulcanization method that is mostly patented in China is known as dynamic desulfurization [16]. In 2019, this was the most common method in China to recycle rubber from end-of-life tires [57]. This devulcanization process differs inherently from the processes investigated in this research. Notably, the rubber in dynamic devulcanization requires heating for almost 3 h, leading to a high consumption of energy [58]. Dynamic desulfurization is the most polluting devulcanization method due to the high processing temperature, toxicity of the components and the use of water [16].

In addition to the differences in method and scale, a respondent in this research also mentioned that energy prices, labour costs and environmental policies and regulations vary in other parts of the world. Under these circumstances, other types of opportunities and barriers might emerge. For a global perspective on devulcanization, follow-up studies might explore the statuses in other parts of the world.

6. Conclusions

This research focused on the implementation of devulcanization as a tire recycling process in Europe. Emerging devulcanization technologies, developed by various organizations, are being applied in several tire recycling processes. To systematically identify the challenges and opportunities associated with devulcanization processes, the Technological Innovation Systems (TIS) framework was applied. The TIS framework, designed to analyze innovation processes, facilitated the adoption of an actor-oriented approach, considering the various perspectives of the organizations involved.

The research showed a range of processing methods within differently organized value chains. This included methods for the collection and sorting of tires, the separation of the tire rubber and devulcanization technologies. The range of value chains and technologies provides opportunities as various types of devulcanized material become available for a range of new applications. However, the diversity of devulcanized materials on the market also causes several barriers because this makes it more difficult for tire and rubber goods manufacturers to compare the different types of devulcanized rubbers on offer. As the devulcanized material from each supplier is unique, manufacturers wishing to substitute virgin rubber with devulcanized material must first engage in additional research and development activities. This leads to additional costs to adapt their compounding process.

The further development of devulcanization technology will aid in the transition to a circular economy but will not resolve the barriers identified in this research. A more systemic innovation at the industry level in tire rubber production and recycling is needed to encourage collaboration among organizations in the production and recycling value chain of passenger car and truck tires. This type of collaboration can make the 'rubber meet the road' by generating optimal devulcanized material for integration into new tires and other rubber products. In the end, although technology innovation plays a role in the transition to a circular economy, collaborative industrial initiatives have the potential to increase the quality and capacity of devulcanization to realize a circular economy in Europe.

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Institutional Review Board Statement: This research proposal, including the interview guidelines, was approved by the Human Research Ethics Committee of the Delft University of Technology on 3 February 2023.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data utilized in this study cannot be made publicly available as it contains proprietary company-specific information.

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Appendix A

Opening statement for the interviews

For the research, semi-structured interviews will be held with representatives of companies in Europe. The representatives from the Netherlands will be interviewed face-to-face, and the representatives of companies elsewhere in Europe will be interviewed by phone or video-calls. The opening statement will be recorded.

My name is Eric Roetman and I am a researcher for Windesheim University of Applied Sciences and a PhD candidate at TU Delft. I am interviewing representatives from European companies that have devulcanised tyres. I would like to interview as a representatives of one of these companies. During the interview I want to gather information about the key activities in the collection, sorting and recycling process for end-of-life tyre recycling by devulcanization. We are both interested in the current situation and what you think that is needed to make a transition to the circular economy.

This interview will start with a set of general questions and then questions will be asked about the key steps in the process: collection and sorting, devulcanization and re-vulcanisation and compounding.

By asking these questions to you and other devulcanization companies, we hope that we can get an overview of the barriers and barriers for devulcanization and the transition to the circular economy. The information will be recorded by a voice recorded and then transcribed (written out on paper). You will receive a copy of the main conclusions and have to opportunity to respond, change or omit misinterpretations. If we want to use non-anonymized quotes, or quotes that traced back to you, from the interview, we contact you and only use these quotes if we have your explicit approval.

The aim of these interviews is to collect data is to publish the outcomes in an academic article and a PhD thesis. The information that is collected, will be dealt with great care and the outcomes will be published in such a way that the information cannot be traced back to you, or another company that is interviewed. Information that can be traced back to you, will not be shared beyond anyone from the research team. The information from the interviews will be stored in a data repository by Hogeschool Windesheim (University of Applied Science). To the best of our ability your answers in this study will remain confidential Your participation in this study is entirely voluntary and you can withdraw at any time.

Appendix B. Interview Topics

The following list of questions was used as a topic guide during the interviews:

General

- What is your position in the company?
- For how many years are you employed by/managing your company?
- How have you been involved with devulcanization in your company?
- Since when have you personally been working with devulcanization?

Company

- What is the mission and vision of your company?
- Is your company part of a holding company and/or part of an international cooperation?
- (How) does your company aims to contribute to the circular economy?

Tyre sorting

- What type of tyre rubber do devulcanize? What is the main source of the rubber (e.g., passenger car, truck, OTR)?
- Do you also devulcanize other sources of rubber than tyres?
- How it the tyre rubber supplied? Do you receive rubber from all brands and types of tyres or or do you choose for specific brands and types of tyres?
- If specific types of tyres are (or should be) used, how is information stored about the tyres?
- Up to what extend should tyres be sorted differently for you to make a transition to the circular economy?

Material handling

- How do you receive the rubber from your suppler (e.g., cut, shredded, granulated?)
- How do you store the rubber before it is devulcanised?
- How do you take action to avoid the rubber to be contaminated or become humid during storage?
- Does the supplied rubber need to be dried?
- Up to what degree does the supplied rubber need extra cleaning or sieving before devulcanization?
- Up to what extent does rubber have to be handled differently if a leap is made to the circular economy?

Characterize rubber and identify unwanted substances

- How do you characterize (measure) the quality of your supply?
- Up to what extend is your supply of tyre rubber of a consistent quality?
- How do you identify unwanted substances in tyre rubber?
- If there are any unwanted substances, what actions do you take?

Separating components of tyres

- Are the specific types of rubber from tyres separated for devulcanization? If so, what equipment is used to separate the tyre rubber?
- Do you, or your suppler, set age limits on tyre rubber for devulcanization? If not, do you believe this will be needed?
- How is (or should) information be provided about the incoming tyres?
- Up to what extend should tyres be separated differently for you to make a transition to the circular economy?

Devulcanization

- What is your definition of devulcanization/vision on devulcanization?
- What type of (devulcanization) technology do you use to devulcanize tyres?
- What types of rubber can be devulcanised with this type of technology? For what purposes is this rubber used?
- For how many years or months have you devulcanised tyre rubber?
- What capacity do you have to devulcanize tyres?
- How many tons of rubber have you processed in the previous year?
- How do you think that devulcanization needs to be further developed to meet the requirement of the circular economy?
- How do you contain the use of energy by devulcanization?

Waste and emissions

- Do you have rubber waste from the recycling process? If so, how could you minimize this waste?
- What actions do you take to avoid any emmission from the devulcanization process?

Allocating devulcanised rubber

- Is the devulcanised rubber blended into a new compoud or is it re-vulcanized without additional rubber or additives? If so, what type of rubber or compounds is added to the mix?
- For what types of products is the devulcanised rubber used? If it is used for tyres, what types of tyres? Agricultural, mining, truck, passenger car?
- What additional requirements from customers do you have to meet because you have included recycled material?
- What would increase the uptake of devulcanised rubber by customers?
- Up to what extent do market demands have to change to shift to the circular economy?

General closing questions

- What are most important oppertunities for sorting and recycling tyre rubber by devulcanization?
- What are the most important barriers for sorting and recycling tyre rubber by devulcanization?
- Is there any information that you would like to add to this interview?

Appendix C. Code Groups

Code Groups	Codes Applied
Supply of end-of-life tyre rubber	Collection of tyres
	Humidity and contaminations in tyre rubber
	Pre-sorting types of tyres (passenger, truck, etc.)
	Selection of specific tyres for devulcanization
	Separate rubber components in tyres
	Supply of rubber (shredded, granulated; age)
Devulcanization process	Definition of devulcanization and standards
	Devulcanization process in use (time)
	Emissions from devulcanization
	Method or technology for devulcanization
	Scale of devulcanization line
Allocating devulcanised rubber	Compounds made with devulcanised rubbers
	Measure quality of re-vulcanized rubber

Code Groups	Codes Applied
Entrepreneurial activities	Business model and organisational structure
	Position of respondent in organisation
Acceptance and creation of legitimacy	Requirements set by customers for dev. rubber
	Uptake of recycled material (in general)
Knowledge development	IP devulcanization process
	Research and development
Knowledge diffusion	Business model and organisational agreements
	Participation of org. in devulcanization projects
Guidance of the search	Perceived barriers for the circular economy
	Perceived opportunities for the circular economy
Market formation	Types of products and markets for devulcanised rubber
	Uptake of devulcanised rubber by customers
Resource mobilisation	Business model and organisational structure
Creation of legitimacy	Requirements set by customers for dev. rubber
	Uptake of recycled material (in general)

References

1. European Commission. Annex I of the plastics strategy. In *List of Future EU Measures to Implement the Strategy*; C.c. Energy, Environment: Brussels, Belgium, 2018.
2. van Langen, S.K.; Vassillo, C.; Ghisellini, P.; Restaino, D.; Passaro, R.; Ulgiati, S. Promoting circular economy transition: A study about perceptions and awareness by different stakeholders groups. *J. Clean. Prod.* **2021**, *316*, 128166. [CrossRef]
3. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32. [CrossRef]
4. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E.J. The Circular Economy–A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
5. Bockstal, L.; Berchem, T.; Schmetz, Q.; Richel, A. Devulcanization and reclaiming of tires and rubber by physical and chemical processes: A review. *J. Clean. Prod.* **2019**, *236*, 117574. [CrossRef]
6. ETRMA. *European Tyre & Rubber Industry Statistics Report*; ETRMA: Brussels, Belgium, 2011.
7. ETRMA. *In Europe 95% of All End of Life Tyres Were Collected and Treated in 2019*; ETRMA: Brussels, Belgium, 2021.
8. Valentini, F.; Pegoretti, A. End-of-life options of tyres. A review. *Adv. Ind. Eng. Polym. Res.* **2022**, *5*, 203–213. [CrossRef]
9. Xiao, Z.; Pramanik, A.; Basak, A.K.; Prakash, C.; Shankar, S. Material recovery and recycling of waste tyres—A review. *Clean. Mater.* **2022**, *5*, 100115. [CrossRef]
10. Noordermeer, J.W.; Dierkes, W.; Blume, A.; van Hoek, H.; Reuvekamp, L.; Dijkhuis, K.; Saiwari, S. Cradle-to-cradle devulcanization options for various elastomer types. *Rubber World* **2020**, *262*, 20–28.
11. Ghosh, R.; Mani, C.; Krafczyk, R.; Schnell, R.; Paasche, A.; Talma, A.; Blume, A.; Dierkes, W.K. New route of tire rubber devulcanization using silanes. *Polymers* **2023**, *15*, 2848. [CrossRef]
12. Saiwari, S.; Dierkes, W. 7-Regeneration and devulcanization. In *Tire Waste and Recycling*; Letcher, T.M., Shulman, V.L., Amirkhanian, S., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 97–129. ISBN 978-0-12-820685-0.
13. Tzoganakis, C. Understanding devulcanization, the path to a circular economy and potential market impact. *Rubber World* **2019**, *5*, 18–22.
14. Markl, E.; Lackner, M. Devulcanization technologies for recycling of tire-derived rubber: A review. *Materials* **2020**, *13*, 1246. [CrossRef]
15. CalRecovery. *Evaluation of Waste Tyre Devulcanization Technologies. Contractor's Report to the Board*; Integrated Waste Management Board, Public Affairs Office: Sacramento, CA, USA, 2004.
16. Wiśniewska, P.; Wang, S.; Formela, K. Waste tire rubber devulcanization technologies: State-of-the-art, limitations and future perspectives. *Waste Manag.* **2022**, *150*, 174–184. [CrossRef] [PubMed]
17. De Jesus, A.; Antunes, P.; Santos, R.; Mendonça, S. Eco-innovation pathways to a circular economy: Envisioning priorities through a Delphi approach. *J. Clean. Prod.* **2019**, *228*, 1494–1513. [CrossRef]
18. Saputra, R.; Walvekar, R.; Khalid, M.; Mubarak, N.M.; Sillanpää, M. Current progress in waste tire rubber devulcanization. *Chemosphere* **2021**, *265*, 129033. [CrossRef] [PubMed]
19. Lacroix, F.; Seghar, S. In-Product-Sorting End-of-Life Tires for Effective Recycling by Devulcanization. In *Tire Waste and Recycling*; Letcher, T.M., Shulman, V.L., Amirkhanian, S., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 130–144. ISBN 978-0-12-820685-0.
20. Lee, H.L.; Schmidt, G. Using value chains to enhance innovation. *Prod. Oper. Manag.* **2017**, *26*, 617–632. [CrossRef]
21. Johansen, M.R.; Christensen, T.B.; Ramos, T.M.; Syberg, K. A review of the plastic value chain from a circular economy perspective. *J. Environ. Manag.* **2022**, *302*, 113975. [CrossRef] [PubMed]
22. Kersker, T.; Kovac, F.; Dague, M. The tire composite. *Fibre Sci. Technol.* **1969**, *2*, 41–57. [CrossRef]
23. Asaro, L.; Gratton, M.; Seghar, S.; Aït Hocine, N. Recycling of rubber wastes by devulcanization. *Resour. Conserv. Recycl.* **2018**, *133*, 250–262. [CrossRef]

24. Winkelman, H.A.; Busenburg, E.B. Effect of Stearic Acid on Reclaimed Rubber. *Ind. Eng. Chem.* **1929**, *21*, 730–732. [CrossRef]
25. Dorigato, A.; Rigotti, D.; Fredi, G. Recent advances in the devulcanization technologies of industrially relevant sulfur-vulcanized elastomers. *Adv. Ind. Eng. Polym. Res.* **2023**, *6*, 288–309. [CrossRef]
26. Van Hoek, J.W.; Heideman, G.; Noordermeer, J.W.; Dierkes, W.K.; Blume, A. Implications of the use of silica as active filler in passenger car tire compounds on their recycling options. *Materials* **2019**, *12*, 725. [CrossRef]
27. Abbas-Abadi, M.S.; Kusenberg, M.; Shirazi, H.M.; Goshayeshi, B.; Van Geem, K.M. Towards full recyclability of end-of-life tires: Challenges and opportunities. *J. Clean. Prod.* **2022**, *374*, 134036. [CrossRef]
28. Lapkovskis, V.; Mironovs, V.; Goljandin, D. Suitability of devulcanized crumb rubber for oil spills remediation. *Energy Procedia* **2018**, *147*, 351–357. [CrossRef]
29. Simon, D.Á.; Bárány, T. Effective thermomechanical devulcanization of ground tire rubber with a co-rotating twin-screw extruder. *Polym. Degrad. Stab.* **2021**, *190*, 109626. [CrossRef]
30. Mangili, I.; Lasagni, M.; Anzano, M.; Collina, E.; Tatangelo, V.; Franzetti, A.; Caracino, P.; Isayev, A.I. Mechanical and rheological properties of natural rubber compounds containing devulcanized ground tire rubber from several methods. *Polym. Degrad. Stab.* **2015**, *121*, 369–377. [CrossRef]
31. de Sousa, F.D.B.; Ornaghi Júnior, H.L. From Devulcanization of Ground Tire Rubber by Microwaves to Revulcanization: A Revulcanization Kinetic Approach Using a Simple Prediction Model. *ACS Sustain. Chem. Eng.* **2020**, *8*, 16304–16319. [CrossRef]
32. Formela, K.; Wąsowicz, D.; Formela, M.; Hejna, A.; Haponiuk, J. Curing characteristics, mechanical and thermal properties of reclaimed ground tire rubber cured with various vulcanizing systems. *Iran. Polym. J.* **2015**, *24*, 289–297. [CrossRef]
33. Chaudhuri, A.; Subramanian, N.; Dora, M. Circular economy and digital capabilities of SMEs for providing value to customers: Combined resource-based view and ambidexterity perspective. *J. Bus. Res.* **2022**, *142*, 32–44. [CrossRef]
34. Petersen, K.J.; Handfield, R.B.; Ragatz, G.L. Supplier integration into new product development: Coordinating product, process and supply chain design. *J. Oper. Manag.* **2005**, *23*, 371–388. [CrossRef]
35. Markard, J.; Hekkert, M.; Jacobsson, S. The technological innovation systems framework: Response to six criticisms. *Environ. Innov. Soc. Transit.* **2015**, *16*, 76–86. [CrossRef]
36. Hekkert, M.P.; Negro, S.O. Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technol. Forecast. Soc. Chang.* **2009**, *76*, 584–594. [CrossRef]
37. Bergek, A.; Jacobsson, S.; Carlsson, B.; Lindmark, S.; Rickne, A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Res. Policy* **2008**, *37*, 407–429. [CrossRef]
38. Musiolik, J.; Markard, J.; Hekkert, M. Networks and network resources in technological innovation systems: Towards a conceptual framework for system building. *Technol. Forecast. Soc. Chang.* **2012**, *79*, 1032–1048. [CrossRef]
39. Markard, J.; Truffer, B. Actor-oriented analysis of innovation systems: Exploring micro–meso level linkages in the case of stationary fuel cells. *Technol. Anal. Strateg. Manag.* **2008**, *20*, 443–464. [CrossRef]
40. Jansma, S.R.; Gosselt, J.F.; de Jong, M.D. Technological start-ups in the innovation system: An actor-oriented perspective. *Technol. Anal. Strateg. Manag.* **2018**, *30*, 282–294. [CrossRef]
41. Planko, J.; Cramer, J.; Hekkert, M.P.; Chappin, M.M.H. Combining the technological innovation systems framework with the entrepreneurs' perspective on innovation. *Technol. Anal. Strateg. Manag.* **2017**, *29*, 614–625. [CrossRef]
42. Chaminade, C.; Edquist, C. From theory to practice: The use of the systems of innovation approach in innovation policy. In *Innovation, Science, and Institutional Change a Research Handbook*; Oxford Academic: Oxford, UK, 2006; pp. 141–163.
43. Lindholm-Dahlstrand, Å.; Andersson, M.; Carlsson, B. Entrepreneurial Experimentation: A Key Function in Entrepreneurial Systems of Innovation. *Small Bus. Econ.* **2019**, *53*, 591–610. [CrossRef]
44. Campbell, S.; Greenwood, M.; Prior, S.; Shearer, T.; Walkem, K.; Young, S.; Bywaters, D.; Walker, K. Purposive sampling: Complex or simple? Research case examples. *J. Res. Nurs.* **2020**, *25*, 652–661. [CrossRef] [PubMed]
45. Knott, E.; Rao, A.H.; Summers, K.; Teeger, C. Interviews in the social sciences. *Nat. Rev. Methods Primers* **2022**, *2*, 73. [CrossRef]
46. Kallio, H.; Pietilä, A.M.; Johnson, M.; Kangasniemi, M. Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *J. Adv. Nurs.* **2016**, *72*, 2954–2965. [CrossRef]
47. Adeoye-Olatunde, O.A.; Olenik, N.L. Research and scholarly methods: Semi-structured interviews. *J. Am. Coll. Clin. Pharm.* **2021**, *4*, 1358–1367. [CrossRef]
48. ISO. ISO 14000 Family. Available online: https://www.iso.org/standards/popular/iso-14000-family (accessed on 12 February 2024).
49. ISO. ISO 9000 Family. Available online: https://www.iso.org/standards/popular/iso-9000-family (accessed on 12 February 2024).
50. Ecovadis. How Does EcoVadis Rate Companies from Industries with High Environmental Impacts? Available online: https://support.ecovadis.com/hc/en-us/articles/4417945610130-How-does-EcoVadis-rate-companies-from-industries-with-high-environmental-impacts (accessed on 12 February 2024).
51. Formela, K. Sustainable development of waste tires recycling technologies—Recent advances, challenges and future trends. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 209–222. [CrossRef]
52. Foschi, E.; Bonoli, A. The commitment of packaging industry in the framework of the European strategy for plastics in a circular economy. *Adm. Sci.* **2019**, *9*, 18. [CrossRef]
53. Kahlert, S.; Bening, C.R. Why pledges alone will not get plastics recycled: Comparing recyclate production and anticipated demand. *Resour. Conserv. Recycl.* **2022**, *181*, 106279. [CrossRef]

54. Lisiecki, M.; Damgaard, A.; Ragaert, K.; Astrup, T.F. Circular economy initiatives are no guarantee for increased plastic circularity: A framework for the systematic comparison of initiatives. *Resour. Conserv. Recycl.* **2023**, *197*, 107072. [CrossRef]
55. Parlement, E. Packaging: New EU Rules to Reduce, Reuse and Recycle. Available online: https://www.europarl.europa.eu/news/en/press-room/20231023IPR08128/packaging-new-eu-rules-to-reduce-reuse-and-recycle (accessed on 15 February 2024).
56. Walker, T.; Gramlich, D.; Dumont-Bergeron, A. The Case for a Plastic Tax: A Review of Its Benefits and Disadvantages Within a Circular Economy. In *Sustainability*; Wasieleski, D.M., Weber, J., Eds.; Emerald Publishing Limited: Leeds, UK, 2020; Volume 4, pp. 185–211.
57. Huang, W. Sustainable management of different systems for recycling end-of-life tyres in China. *Waste Manag. Res.* **2021**, *39*, 966–974. [CrossRef]
58. Li, X.; Xu, H.; Gao, Y.; Tao, Y. Comparison of end-of-life tire treatment technologies: A Chinese case study. *Waste Manag.* **2010**, *30*, 2235–2246. [CrossRef]