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Towards Sustainability in the Automotive Industry – Circular Economic Practices of the Audi Group

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Circular Economy is an economic concept that aims to maximise resource efficiency and minimise waste generation by recycling, reusing, remanufacturing, and repairing products to extend their lifespan and extract maximum value from them. Historically, the automotive industry has not focused on sustainable practices. In the last decade, automotive manufacturers have increasingly adopted circular economy practices driven by a combination of environmental concerns, resource scarcity, regulatory pressures, consumer demand, and the pursuit of new business opportunities. By embracing circularity, the industry aims to reduce its environmental impact, optimise resource use, and build a more sustainable and resilient future. The paper provides a review to present the concept of circular economy and to evaluate its current state in the automotive industry. The case study aims to provide a glimpse into the initiatives and strategies being made by the Audi Group to become circular. The research is descriptive and includes mainly qualitative methods using a content analysis of corporate sustainability reports, websites, and interviews to gather data.

1. Introduction

A circular economy (CE) or closed-loop economy has gained the interest of both scholars and practitioners because it is seen as a new business model expected to integrate economic activity and environmental well-being in a sustainable way (Murray et al., 2017). CE promotes maximum reuse/recycling of materials, goods and components in order to decrease waste generation to the largest possible extent. The traditional, linear economy (the so-called "take, make, and dispose") is a one-way system converting natural resources into waste via production (Sari et al., 2021). It fails to take into account the limited and exhaustible nature of natural resources (Ghisellini et al., 2016). The circular economy is envisaged as having no net effect on the environment; rather, it restores any damage done in resource acquisition while ensuring that little waste is generated throughout the production process (Murray et al., 2017). However, in practice, resource use is very often neither fully circular nor fully linear. (Korhonen et al., 2018).
There is no single and commonly accepted definition of the CE concept. The most employed definition has been provided by the Ellen MacArthur Foundation: "[CE is] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals that impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (EMF, 2013).
Although certain authors equate CE entirely with recycling, and they have considered it only as an approach to more appropriate waste management, it must be underlined that this is a very limited point of view. According to the most common conceptualisation, a circular economy emerges through three main actions: Reduction, Reuse, and Recycling (Ghisellini et al., 2016). In most of the definitions, the focus is on reuse and recycling. The 3R framework was soon completed with a fourth R (Recovery), but it did not become so widespread. Scholars have proposed further R frameworks, which are considered the 'how-to' of CE and its core principle. The most nuanced 9R framework by Potting et al. (2017) serves as a starting point for our analysis. It presents a range of strategies ordered from high to low circularity (see Table 2; the meaning of each R is explicated in the text). Kirchherr et al. (2017) stated that in the past decade, the academic discourse moved away from the R

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frameworks towards a system perspective. Several authors highlight that CE requires a broader and much more comprehensive look and a fundamental shift instead of incremental twisting of the current system.
The innovation point of the paper lies in the presentation and evaluation of the circular practices of the Audi Group in a systematic way, which means using the 9 R model of Potting et al. (2017). Although the company applies several circular solutions in its production processes, a structured approach to the activities highlights that primarily activities with a low level of circularity are present in its practices. The paper is divided into three main parts. First, we give an overview of the concept of the circular economy. Next, we focus on its current state in the automotive industry. Finally, our case study aims to present the circular strategies being made by the Audi Group.

2. Automotive industry and circular economy

The global automotive sector is one of the world's largest industries, accounting for around 3 % of the world's total GDP. Manufacturing vehicles is also inherently resource intensive: automotive steel and aluminium are responsible for nearly 12 % and 27 % of respective global use for each material (Aguilar Esteva et al., 2020). According to OICA, in 2022, 85 million new vehicles were produced, an increase of 6 % compared to 2021. The majority of the automotive businesses follow a linear approach, meaning that once a vehicle reaches its end-of-life, many of the components of the car will end up in landfills. The automotive industry is one of the main contributors to the global environmental crisis and requires a radical shift in the way it performs business (Del Angel Hernandez and Bakthavatchaalam, 2022).
More recently, the automotive industry has been reshaped by several trends, such as electrification, the sharing economy, and autonomous driving (Urbinati et al., 2021). The main interest of the sector is in the issue of emissions, thus on the powertrain (batteries and motors), leading to a continuation of production without addressing the environmental pressures of the whole industry. As a result, the topic of circular economy is not at the centre of research and development activities (Valladares Montemayor and Chanda, 2023).
The transition process from linear economy to CE has brought many challenges and barriers. However, at the same time, it offers several opportunities (new sources of revenue) for automotive companies. Focusing mainly on barriers to the circular economy, Jaeger and Upadhyay (2020) point out that the companies currently implement CE actions with low or very low effects: they focus on recycling and reducing waste. Among the identified barriers, first, they mention high start-up costs. Recycling requires a technology-intensive process that needs high-level testing protocols to ensure the appropriate quality of the recycled materials. Coordination problems between companies can also be a barrier. Urbinati et al. (2021) examined the possibilities of the introduction of circular business models (CBMs) in the automotive industry, and they pointed out that the main challenge is the closure of the loop involving the final customers. The relatively long lifecycle of a car and the existence of a well-established second-hand market increase the chances for original equipment manufacturers to lose control over the customer and over the product. Product-related barriers mainly refer to low-returned product quantity and product quality, while among company-related barriers, they mention high investment costs and the time needed to break even.
Nevertheless, automotive manufacturers are increasingly exploring extended circular economy strategies to enhance the sustainability of their products. By becoming circular, companies would reduce their dependence on resources and susceptibility to material price fluctuations. Governments have started to implement regulations and restrictions around emissions, waste, and energy use, which would further incentivise switching to CE. Many of these actions target recycling, reuse and remanufacturing. However, CE is a much more complex system (Del Angel Hernandez and Bakthavatchaalam, 2022). Patel and Singh (2022) list three circular strategies deployable in the manufacturing phase: material replacement from virgin to recycled materials, product designing to facilitate ease of disassembly and consolidation of parts and use of life-cycle analysis tools for developing innovative materials with minimum impact on economy and environment. Valladares-Montemayor and Chanda (2023) analyse the circular initiatives implemented by the top 10 automotive companies on the Fortune 500 list. They propose a four-level framework to evaluate the circular efforts of the examined companies, which is also applied in this paper when evaluating the circular practices of the Audi Group. They stated that despite the steps which have been taken by the industry, it is far from what is needed to have long-term and impactful sustainable solutions.

3. The circular practices of the Audi Group

The Audi Group, comprising Audi, Lamborghini, Ducati and Bentley, is a manufacturer of automobiles and motorcycles in the premium, luxury and supercar segments. The Premium brand group is managed by Audi AG, a wholly owned subsidiary of the Volkswagen Group since 2020. With its sales partners, the Audi Group is present in more than 100 markets around the world and operates at 22 locations in 13 countries with its production partners. The head office is located in Ingolstadt (Audi Report 2022).

Audi is evaluating and following a number of different approaches for implementing closed cycles in the automotive value chain. In this paper the circular practices of the Audi Group are presented in a four-level framework proposed by Valladares Montemayor and Chanda (2023). The system is based on the 9 Rs of circularity (Potting et al. 2017). It is considered that refuse, rethink and reduce (R0, R1 and R2) are preventative measures before any use of materials. They are prerequisites to transition from a linear to a circular economy for any multinational enterprises. Thus, they represent the Level 0 of circularity. The further levels of circularity correspond to the following actions:

Level 1: reuse, refurbish, repair (R3, R4, R5)

Level 2: remanufacture and repurpose (R6, R7)

Level 3: recycle (R8)

Level 4: waste management and recovery residual management (R9)

3.1 Preventative measures – the Level 0 of circularity

The three preventative measures are related to the pre-use phase. „Refuse” means that the company offers the same function with a radically different product. In the automobile industry, the shift from gasoline and diesel models to electric vehicles (EVs) can be considered as an example. The Audi Group manufactured 1,717,896 vehicles in 2022, an increase of 8.6 % compared to the previous year. The production of fully electric vehicles increased significantly to 127 927 vehicles despite the persistently tense supply situation. On the other hand, the number of plug-in hybrids (PHEV) produced decreased to 74,227 units, above all due to shortages in the supply of parts. The share of fully electric vehicles and plug-in hybrids in total car production of the Audi Group amounted to 11.8 %, 202 154 vehicles (Audi Report, 2022). From 2026 on, all new models from the brand worldwide will be fully electric. The company will gradually phase out the production of vehicles with combustion engines by 2033, which highlights the importance of the incorporation of circularity in the production of EVs. „Rethink” means a more intensive product use present in the company's practice by the Audi on-demand car rental service aiming to reserve a car in a few seconds.

Among the preventative measures, reduction is by far the most common practice. In 2022, the Audi Group succeeded in reducing its water consumption significantly compared with the previous years. There are several reasons for this decrease: the application of state-of-the-art water-saving technologies, weather-related reasons (reduction in cooling requirements), but the repair of leakages can also be mentioned. As a result of the new recycling options identified, Audi has succeeded in reducing the volume of waste per vehicle. In 2022, 274,118 t of metallic waste were generated throughout the Group, all of which are destined for recycling. The volume of waste - excluding metallic waste (scrap) - was up due to optimised data collection, but as much as 97 % of this waste was recyclable. By increasing the share of recycled aluminium, Audi avoids the energy-intensive production of new aluminium. In this way, a net total of more than 195,000 t of CO_2 was avoided in 2021 (Audi Report, 2021).

Table 1: Reduction activities: the total freshwater consumption, the volume of waste per vehicle and the avoided CO_2 emissions of the Audi Group, Source: Audi Report 2021, Audi Report 2022

	Total fresh water consumption (m³)	Metallic waste (scrap), t	Total volume of waste (excl. scrap), t	Recyclable waste, t\	Avoided CO_2 emissions, t
2019	3,428,689	320,793	107,940	104,096	150,000
2020	3,133,474	273,656	100,035	95,229	165,000
2021	2,940,094	269,328	97,446	94,296	195,000
2022	2,914,278	274,118	188,666	183,467	no data available

Rising energy prices in 2022 have increased the pressure on the company to achieve greater energy independence by finding optimal solutions for producing renewable electricity and heat. Decarbonizing the logistic chain by shifting more from road to rail also promises substantial reductions in CO_2 emissions. The use of biogas or electric trucks as the most climate-friendly transport technologies is also on the agenda (Audi Report 2022). One of the central goals of the company is the decarbonization of the production process and logistics in order to achieve the target of carbon neutrality at Audi production sites by 2025. This goal has already been completed for Audi Brussels and Audi Hungaria in Győr, the degree of carbon neutrality is 60 % at Neckarsulm site and 75 % in San José Chiapa and in Ingolstadt (Audi Report, 2022).

3.2 Level 1 activities

The first level of circularity involves reusing (the reuse of a discarded product by another consumer while it is still in good condition and fulfilling its original function), refurbishing (bringing an old product up to date) and repairing (the maintenance and repair of a product so that it can be used in its original function) (Potting et al., 2017). The reuse activity appears in the production process concerning water usage. Water is reused multiple times within a plant (Audi Report, 2021). The other Level 1 activities are primarily related to the use phase. Therefore, they are not typical for the production stage.

Table 2: Circular efforts at the Audi Group, Source: the authors' research based on Audi Reports and on Potting et al. (2017)

Levels	Activities	Subjects	Methods
Level 0	refuse (R0)	Gasoline and diesel models	increased number of fully EVs
	rethink (R1)	Audi on demand	car sharing
	reduce (R2)	the use of fresh water	technical solutions, weather-related reasons, repair of leakages, increased use of rainwater, no use of drinking water in the production
		the volume of waste per vehicle	new recycling options
		CO_2 emissions	reprocessing of aluminum waste, shifting more from road to rail, the use of low and renewable CO_2 energy sources
Level 1	reuse (R3)	water	multiple times within the plant
	repair (R4)	-	
	refurbish (R5)	-	
Level 2	remanufacture (R6)	damaged automotive glazing	to produce new windshields
		lithium-ion batteries in good condition	as a replacement part in an electric vehicle
	repurpose (R7)	recycled PET-bottles, textiles or residual fibres	Dinamica microfibre used for seat upholstery
		lithium-ion batteries in a fair to good condition	have a second life outside an electric vehicle
		plastic waste	different assembly tools created by 3D printer
Level 3	recycle (R8)	metal	turned into structural steel via downcycling
		aluminium	the offcuts are sorted by grade and returned to the suppliers to produce new aluminium coils of the same quality
		plastic	for processed plastic: shredded and converted into synthetic granulate - for not safety-relevant parts
			for mixed plastic: using a thermochemical conversion process, pyrolysis oil is produced – for a high-quality product, even for safety-relevant parts
		diverse materials (glass, aluminium, plastic, steel)	recycling 100 end-of-life vehicles in collaboration with partners (experimental project)
		lithium-ion batteries in poor condition for continued road use	broken down, sorted into individual fractions and then reprocessed
Level 4	recover (R9)	diverse materials	incineration

3.3 Level 2 activities

Level 2 involves remanufacturing and repurposing. During remanufacturing, the parts of a discarded product are used in a new product with the same function. This process allows, for example, automotive glass that can no longer be repaired to be reused to produce new windshields. Less energy and fewer raw materials (quartz sand, for example) need to be used overall to produce new windows. In addition, up to 30 % less carbon dioxide is emitted during remanufacturing when compared with producing new glass. The lithium-ion battery is the central element and largest component of an electric car. When the electric vehicle reaches its end of life, disposal does not make sense either economically or ecologically. Depending on the remaining capacity identified by the test system, the high-voltage battery can be used for one of three different purposes:

remanufacturing, repurposing and recycling. The lithium-ion batteries in very good condition can be remanufactured and reused as a replacement part in an electric vehicle. (Audi Report, 2021).
Audi implements a repurposing activity, which means that the discarded product or its parts are used in a new product with a different function. If the lithium-ion battery of the electric car is still in fair to good condition, it can have a second life outside an electric vehicle. From recycled PET bottles, textiles, or residual fibers, the company prepares a resource-friendly, microfibre, non-woven material named Dinamica. It was introduced as a seat upholstery option in 2020 and has since become available for many models (Audi Report, 2021). Packaging also serves as raw material for more than 160 assembly tools created by 3D printers. In this way, employees not only get tools that are tailored precisely to the task at hand. (Audi Report, 2021).

3.4 Level 3 and Level 4 activities

Recycling activities are considered any recovery operations by which waste materials are reprocessed into products or materials, whether for the original or other purposes. In many cases, the qualitative properties of the new product made from recycled material are lower than those of the original product. This phenomenon called downcycling appears if, for example, the metal from end-of-life vehicles is turned into structural steel or if car windows are remanufactured to become water bottles or insulating materials. In certain cases, recycling is possible without loss of quality, for example, in the Aluminium Closed Loop and in the recently established Plastic Loop project of Audi (Audi Report, 2022).
Audi began to use aluminum as a body material in 1994. The material has been used in increasingly more model lines for over 25 y. Nowadays, Audi and its suppliers are able to recycle aluminum offcuts into materials with the same quality as new ones. The offcuts produced are sorted by grade and returned to the suppliers. It is then used to produce new aluminum coils of the same quality that Audi then reintroduces into the production process. This closed material loop process has been used since 2017 in increasingly more plants over the years, currently in Ingolstadt, Neckarsulm, Győr, and Bratislava (Audi Report, 2021).
Processed plastics derived from a recycling process are being used in more and more vehicles. After they have been shredded and separated from other materials, plastic parts can be converted into synthetic granulation. This mechanical recycling usually reaches its limits when mixed plastic waste is processed, and different adhesives, fillers, or lacquers are used. In addition, the quality of the plastics decreases with each mechanical processing step to the extent that it can generally no longer be used in vehicle construction especially not for safety-relevant parts (Audi Report, 2021).
For the mixed plastic waste that cannot be sorted by type and can also contain foreign substances and lacquers, chemical recycling can be a solution. Using a thermochemical conversion process, pyrolysis oil is produced at a temperature of 500 degrees Celsius. Then, pyrolysis oil can be used to produce plastic components of the same high product quality as new products. This recycled plastic can even be used for safety-relevant parts. In the framework of the PlasticLoop project, the plastic covers for the seat belt buckles of the Audi Q8 e-tron model are produced from recycled plastic (Audi Report, 2022).
Audi intends to increase the use of secondary materials, especially post-consumer recycled materials from end-of-life vehicles, in its new vehicles. There are also statutory requirements relating to this important topic: the German End-of-Life Vehicle Ordinance. Direct access to secondary materials could lead to improved certainty of supply in the future. In the MaterialLoop project launched in 2022, Audi is recycling 100 end-of-life vehicles in collaboration with its partners and analyzing how the four material groups (glass, aluminum, plastic, and steel) can be reused in the production of new vehicles (Audi Report, 2022).
Batteries whose condition is too poor for continued road use are first preconditioned (discharging, dismantling). The energy storage units are carefully broken down by mechanical processes and sorted into individual fractions such as aluminum, copper, plastics, and „black powder" for recycling. The black powder contains valuable raw materials for batteries, like lithium, nickel, manganese, cobalt, and graphite, which are separated by type by specialist partner companies using hydrometallurgical processes. These are then reprocessed in subsequent process steps into new cathode material, among other things (Audi Report, 2022). If waste can no longer be used for materials recycling, then it can be incinerated and used as energy in the form of heat and/or electricity. This process represents Level 4 of circularity in this framework.

4. Conclusions

Circular economy contrasts with the traditional linear business model, which focuses on large quantities of easily accessible raw materials and low-priced energy. Closed material cycles are one of the most effective tools for improving sustainability in the automotive industry. They enable the decoupling of economic growth from the consumption of resources and also reduce dependencies. There is only a little research analyzing the current circularity efforts being made by the industry, and the academic literature is highly lacking. Instead, automotive research and development are centered on the powertrain. However, understanding the circularity efforts and initiatives across the industry is important in order to reduce the knowledge gap and to get to know best practices.

This paper provides an insight into the circular practices of the Audi Group. Analyzing the official documents, it has been observed that Audi is following a number of different approaches to implementing closed cycles in the automotive value chain. Much of the work is being done around the 3 original Rs, reducing, remanufacturing/repurposing, and recycling. Applications of Level 1 activities (reuse, repair, and refurbish) are rare because they are related primarily to the use phase and not to the production process. The increasing importance of circular practices is also indicated by the fact that not only the individual Audi production sites have started to network with each other in order to share their own solutions for reducing waste, but the company has elaborated its circular strategies in close collaboration with its suppliers. Unfortunately, the annual sustainability reports of the automotive companies do not provide the opportunity to collect comparative data. We have only limited ideas about the real extent of their circular practices.

Nevertheless, the true potential of the circular economy is far from being exhausted in the automotive sector and at the Audi Group as well. To truly become more sustainable and circular, the sector and the company need to handle all components of the car, manufacturing, and design. Even though the current and planned R&D projects of the examined company are not publicly available, there is evidence of plans that aim at the extension of circular activities (MaterialLoop). Also, the transition to the production of electric vehicles needs the continuous review and actualization of circular practices.

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