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Moving towards a circular pressure vessel economy in mobility application in Sweden

How can information exchange help?

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Abstract

Transition to vehicles with reduced-emission fuels such as Compressed Natural Gas (CNG), LNG (Liquified Natural Gas), Biogas, and Hydrogen gas is an important sustainable approach in the mobility industry. The pressure vessels which are installed as the fuel container on such vehicles are the critical component in this transition. However, the Type IV Carbon-Fibre-Reinforced Plastics (CFRP) pressure vessels are made from carbon and energy-intense materials while the current End-of-Life (EoL) treatment method is incineration and landfills, which creates huge resource waste and pollution. Circular Economy (CE) is an approach to optimize resources and minimize material waste. Effective data, information, and knowledge exchange among key stakeholders in the value chain has been identified as a catalyst for advancing CE initiatives. This research explores existing circular economy strategies within the pressure vessel industry in mobility application, as well as identifies external factors influencing these strategies using the PEST framework. The research also pinpoints critical actions and information needs to understand how inter-corporation information and knowledge exchange can foster CE actions. The study involved 15 interviews with key stakeholders across the pressure vessel value chain, including pressure vessel producers, vehicle workshops, dismantlers, recyclers, and trading platforms. Complementary information was gathered through a literature review. The study discovers that the reuse and recycling actions are the current CE actions for Type I metal pressure vessels while the eco-design and potential recycling are the current CE initiatives for Type IV Carbon-Fibre-Reinforced Plastics (CFRP) pressure vessels. Barriers include stringent inspection requirements, inadequate EoL volume of pressure vessels, low acceptance and safety concerns regarding reused and recycled materials, and the technical challenges of downcycling. Opportunities include upcoming regulations such as the End-of-Life Vehicle Directive and Extended Producer Responsibility on vehicles, the high residual value of the raw material, the social pressure on utilizing recycled materials and the recycling technical innovation. The critical information includes market information about supply and demand, technology information about the lifespan, dismantling manuals, identification and quality, and regulation information regarding the inspection and dismantling regulations.

Keywords: Pressure vessel, Circular Economy, Information sharing, Mobility

Executive Summary

Background

Using reduced-emission fuels such as Compressed Natural Gas (CNG), Liquid Natural Gas (LNG), Biogas, and Hydrogen is considered an important approach to reducing carbon emissions from road transportation. The alternative fuel has to be stored in pressure vessels which hold the gas and liquid at a pressure substantially different from the ambient pressure. There are two types of pressure vessels widely used in vehicles, Type I is constructed fully of metal steel, and Type IV is one type of composite called Carbon-Fibre-Rei,nforced Plastics (CFRP). With the projection of a growing amount of Hydrogen fuel cell vehicles, the amount of Type IV CFRP pressure vessels that stand out for their lightweight and large storage capacity is expected to grow rapidly in mobility applications.

However, the pressure vessel industry is growing rapidly but linearly. The Type IV CFRP pressure vessels are mainly made from carbon and energy-intensive raw materials such as carbon fiber, High-density polyethylene (HDPE) inner, and epoxy resins like thermoset or thermoplastics. The main material carbon fiber is 10 times more carbon-intensive than conventional steel production (Kawajiri & Sakamoto, 2022). Due to the lack of regulation and recycling technology on composite, most of the Type IV CFRP pressure vessels are currently landfilled or incinerated, which leads to huge material loss and pollution. The Circular Economy is an approach to optimize resources and minimize material waste, and there are huge opportunities to make pressure vessels in mobility applications more circular thanks to their long lifetime, valuable materials, and merging recycling technology innovations. The exchange of data, information and knowledge among key stakeholders has been proven as the catalyst for promoting circularity. However, there is a lack of academic attention on the circularity of pressure vessels in the mobility application and the relation between information sharing and circularity.

Research aim and approach

The research aims to firstly discover the current circular economy strategies in the pressure vessel industry in the mobility application as well as identify the external factors influencing these actions. Secondly, identify how inter-corporation information and knowledge exchange could promote such circular economy actions. This research focuses on the Type I metal pressure vessels and Type IV Carbon-Fibre-Reinforced Plastics (CFRP) pressure vessels. The geographic scope is Sweden, and the types of vehicles include CNG, LNG, Biogas, and Hydrogen gas vehicles, mainly passenger cars, buses, and trucks.

To achieve the research aim, the research questions are as bellowed:

RQ1 What are the existing circular economy strategies in the pressure vessels industry in mobility applications and why?

RQ2 What are the key action points and the data needs for the actors in the value chain to conduct such circular economy strategies?

The result of the study is expected to discover how information exchange could promote more circular economy actions in pressure vessels in mobility applications. The methodology of the study is qualitative. To answer the first research question, the data is collected from interviews with the key stakeholders in the pressure vessel industry in mobility applications as well as

literature reviews of related regulations, reports, and press articles. The PEST framework is used to analyze the external challenges and opportunities influencing the circular economy strategies from politics, economics, social norms, and technology aspects. To answer the second research question, the data is collected mainly from interviews with the key stakeholders in the pressure vessel value chain, including pressure vessel producers, vehicle workshops, vehicle dismantlers, and recyclers. The data is summarized by themes and patterns qualitatively. Fifteen interviews were conducted in the forms of online meetings, email, and on-site.

Findings

RQ1 What are the existing circular economy strategies in the pressure vessels industry in mobility applications and why?

For the Type I metal pressure vessels, the existing CE actions are recycling and reuse, and recycling is dominating while only very few get reused. The reasons for such a scenario are, from a regulation aspect, the inspection requirements on the pressure vessel are strict, which means that only a limited volume of used pressure vessels is reusable. From the economic side, because most of the EoL gas vehicles are exported, the domestic supply of used gas vehicles and pressure vessels is very small so it's hard for customers to find matching pressure vessels. The used pressure vessels also do not have a bigger price advantage compared to the new pressure vessels. The cost of the virgin metal material is affordable while the transaction cost of the used pressure vessels adds extra costs. From a social and organizational norms perspective, the safety concern of the used pressure vessels decreases the acceptance of reusing actions and the vehicle dismantlers also lack the market demand information. From a technical side, some pressure vessels are not designed for durability, and the used pressure vessels are not reusable because the low quality could not fulfill the inspection requirements.

For the Type IV Carbon-Fibre-Reinforced Plastics (CFRP) pressure vessels, the existing CE actions are mainly from the Eco-design of pressure vessel producers to reduce the complexity of the material as well as integrate recycled carbon fiber and recyclable resins. The reason for this scenario is mainly because of the low volume of the EoL pressure vessel currently on the market and the underdevelopment of the recycling market. The challenge and barriers to developing recycling include that, from the regulation side, the lack of waste management regulations and circular requirements on the composite makes the responsibility unclear. From an economic aspect, the volume of EoL pressure vessels currently is very small and hard to predict because the pressure vessel producers are not willing to disclose the production data as well as the long lifespan of pressure vessels. From the social and origination norms aspect, the quality and safety concern of the recycled carbon fiber leads to low acceptance of using the recycler carbon fiber, and the negative perspective of considering the pressure vessel as waste makes the unwillingness to disclose the production volume. There is also a lack of business cases showing the economic feasibility of using recycled carbon fiber. From the technology aspect, the downcycling of the carbon fiber is still a technology challenge, and using the recycled carbon fiber may risk the original design and production of pressure vessels.

On the opportunity side, the upcoming End-of-Life Vehicle Directive (ELV) will require sustainable waste treatment and set recycling targets for plastics. Extended Producer Responsibility (EPR) also requires the vehicle producers to disclose information such as the construction of components, dismantling and EoL treatment guidelines, and the possibility of recycling and reuse. From the economic and market aspect, the market of hydrogen vehicles and the pressure vessel is expected to grow rapidly, the growing supply-demand gap of virgin carbon fiber will make recycled carbon fiber a feasible option for pressure vessel producers. The high residual value of the EoL pressure vessel will create economic incentives for collecting and recycling them. From the aspect of social and corporate norms, the usage of virgin carbon fiber leads to a high carbon footprint of the pressure vessels, which will create a negative corporate image for pressure vessel producers. Moreover, the sustainable narrative of the whole hydrogen economy will require the pressure vessel industry to be sustainable. Finally, there are many ongoing technological innovations in solving the downcycling problem of carbon fiber and some of them have already succeeded.

RQ2: What are the key actions and data needs for the actors in the value chain to conduct such CE strategies?

In terms of recycling actions of Type I metal pressure vessels, the key actions are the dismantling process and the most critical information is the technology guidelines and regulation requirements on the dismantling process, and the market information about the material inflow and outflow is not a critical since the pressure vessel is considered as a scrap. In terms of the reusing actions of Type I metal pressure vessels, the critical information for dismantlers is the market information about the demand, which is the prerequisite for the dismantlers to consider the used pressure vessel as a profitable spare part. The second critical information is the regulation, especially the inspection requirements serve as a protocol for dismantlers to decide the reusability of the pressure vessels. the requirement to disclose the manufacturing date of the pressure vessel also provides lifespan information for dismantlers. The third critical information is that for workshops and gas vehicle users to purchase used pressure vessels instead of virgin ones, the market information about the suppliers and the technology information about the used pressure vessels are critical. For the brand-owned workshops and dismantlers, an internal information platform is a channel for exchanging such information, and it's relatively easier to identify the matchingability of the demand and supply. For the independent dismantlers, the third-party spare part trading platform is the main channel for information exchange and the identification information is the most needed information to reduce the transaction costs.

In terms of the potential recycling action of Type IV Carbon-Fibre-Reinforced Plastics (CFRP) pressure vessels. The critical information for the dismantler is the market information about the downstream recyclers and the residual value of the used pressure vessels. The critical information for recyclers is the design information of the pressure vessel, which helps them unwind the material more efficiently. For the end-user pressure vessel producers, the critical information is the quality and cost information of the recycled carbon fiber. To develop the recycling market, all the actors in the value chain should be informed with the regulation information about the responsibility allocation, the expected growing volume of EoL pressure vessels and the development of the recycling technology.

Conclusion and suggestion

The study shows that the critical actors who are directly involved in the reuse and recycling actions of pressure vessels in the mobility application include pressure vessel producers, workshops, dismantlers, and recyclers. Even though certain actors like public authorities, vehicle producers, and spare part trading websites are not directly involved in CE actions, they are the main source of the information. The critical type of information includes market information about supply and demand, technology information about the lifespan, dismantling manuals, identification and quality, and regulation information regarding the inspection and dismantling regulations.

The suggestion for encouraging the market information flow is to enhance the search and matching algorithms in the trading platform as well as provide identification information like series numbers. The dismantler and gas industry could help with spreading the regulation information and making it more accessible. Regarding the technical information, the EPR and ELV require the vehicle producers to disclose information on the construction of components, dismantling and EoL treatment guidelines, and the possibility of recycling and reuse, which could hugely promote circularity.

To develop the recycling market for Type IV Carbon-Fibre-Reinforced Plastics (CFRP) pressure vessels, information about the growing volume of EoL pressure vessels, the technology feasibility of recycling pressure vessels, and the economic feasibility of recycling the pressure vessels should be shared. The pressure vessel producers should change the negative narrative regarding the EoL pressure vessels and disclose the production volume, the technology feasibility of recycling pressure vessels should be promoted by the technology innovator, composite association, information-sharing platform, and the government. The economic feasibility of recycling the pressure vessels also needs to be promoted by business cases and examples.

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Abbreviations

CE: Circular Economy

EoL: End-of-Life

CFRP: Carbon Fiber Reinforced Plastics

CNG: Compressed Natural Gas

LNG: Liquid Natural Gas

HFCV: hydrogen Fuel Cell Vehicles

FCEV: Fuel Cell Electric Vehicle

Extended Producer Responsibility (EPR)

End-of-Life Vehicle Directive (ELV)

Corporate Sustainability Reporting Directive (CSRD)

1 Introduction

1.1 Problem definition

The Pressure vessel is a fuel container designed to store the gases or liquids at a pressure substantially different from the ambient pressure. The main application for pressure vessels is to serve as gas storages for fuels such as Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), Biogas, and Hydrogen gas (H2). For household applications, CNG cylinders are used for heating and cooking (Borg, 2019). For industry applications, CNG fuel storage systems are provided to medium- and heavy-duty original equipment manufacturers like forklift trucks and lawn-mowing (Hexagon, 2020). For the mobility industry, pressure vessels can serve as fuel storage tanks installed in vehicles like passenger cars, buses, and trucks as well as in distribution systems like refueling stations.

Based on their construction materials, there are four types of commercial pressure vessels, Type I, Type II, Type III, and Type IV. Except for Type I is constructed fully of metal steel or aluminium, the remaining three types of pressure vessels contain composite material either as linear materials or wrapped cover (Sloan, 2023). Composite materials are a large family of heterogeneous materials composed of more than two or more phases, and Carbon-Fibre-Reinforced plastics (CFRP) are one type of composite that is mainly composed of carbon fiber, resin matrix, and other materials(Colledani & Turri, 2022). Due to the merits of high strength, large containing capacity, and low weight, CFRP is the most important material for Type III and Type IV pressure vessels (J. Zhang et al., 2023). The Type I and Type IV pressure vessels are most commonly used in vehicles.

The pressure vessel market is growing and the biggest driver is the global commitment to combat climate change by switching to renewable and reduced-emission fuel. The mobility industry is paying more attention to the pressure vessel industry since there is a bigger demand for them to switch to reduced-emission fuels. With more passenger cars, buses, and trucks designed to be fueled by CNG and H2, the demand for pressure vessels, which is the key component for fuel storage is growing in the mobility sector. U.S Commercial Service (European Commission, 2024) estimated that there will be 2 million hydrogen vehicles equipped with pressure vessels by 2030, and the amount of pressure vessels is expected to be 4 million in Europe.

However, the pressure vessel industry itself is developing unsustainably even though it’s considered a key enabler for fuel switching in the mobility sector. One of the biggest problems of the pressure vessel industry is that the raw material of pressure vessels is very carbon-intensive while the industry is developing linearly. The CFRP pressure vessels are manufactured from carbon-intense materials but are not designed for circularity. The CO2 emission related to carbon fiber production is estimated at 25kg Co2 eq per kg, which is about 10 times higher than conventional steel production (Kawajiri & Sakamoto, 2022). 10 kg of carbon fibre is required to produce 1 kg of a pressure vessel of 700 bar average, while the carbon footprint of 1 kg of carbon fibre is around 25 kg of Co2 emission, the production of a 5 kg hydrogen tank at 700 bar will require 50 kilograms of carbon fibre, which contributes to about 1250 kg of CO2 emission(Sloan, 2023).

The emission from carbon fibre production is only a part of the carbon footprint of pressure vessels’ whole life cycle. The linearly growing pressure vessel industry leads to huge CO2 emissions and a waste of resources. Another environmental concern of the industry is the mismanagement of End-of-life pressure vessels. Due to the lack of regulations and recycling technology, most of the pressure vessels end up in landfills or incineration after the end of life, which causes related water and air pollution and consequently damages the health of the environment and a huge loss of resources. With a growing demand for pressure vessels in mobility applications, the waste of materials and environmental damage will be more impacting if the industry continues growing linearly.

On the other hand, there are huge opportunities to make pressure vessels in mobility applications more circular because of their long lifetime, valuable materials, and merging recycling technology innovations. The average lifetime of the pressure vessel is from 10 to 20 years, which means it could potentially outlive the lifespan of the vehicle and be reused into another vehicle. Therefore, pressure vessels have a huge potential to be reused. Moreover, materials such as carbon fibre could potentially be recycled and used in manufacturing new pressure vessels because of the development of technological innovation. Additionally, the high residual value of the material such as carbon fiber also provides huge financial incentives for reusing and recycling. In summary, the long lifespan, highly valuable materials of CFRP pressure vessels, and new recycling technology create huge potential to encourage more reuse and remanufacture actions in the pressure vessel industry in the mobility sector.

1.2 Aim and research questions

The exchange of data, information, and/or knowledge among independent organizations has been discovered as the catalyst for advancing circularity, as proved by many studies in agriculture, construction, and the electronic industry (Ersoy et al., 2022; Fargnoli et al., 2019; Koppelaar et al., 2023). Actors in the value chain such as suppliers, manufacturers, distributors, users, service providers, and recyclers can make feasible circular decisions based on the information inflow shared by other actors as well as make information outflow to influence other actors. Information and knowledge such as product-related information, location-related information, utilization-related information, legislative information, market information, and process information are considered resources for corporations by setting the foundation to make circular decisions(Ferguson & Browne, 2001).

For example, manufacturers can design products more sustainable(Scruggs et al., 2016) and prevent overproduction(P. Zhang & Xiong, 2017) based on the feedback information shared from downstream actors. Service providers can improve the quality of maintenance service (Fargnoli et al., 2019) and make preventive maintenance based on the information shared by manufacturers and users(Metso et al., 2018). Recyclers can identify the valuable components more quickly and manage the waste more safely for workers based on the information shared by suppliers and manufacturers (Nowakowski, 2018). Generally, information sharing could help all the actors in the value chain foresee future changes in the market or policy landscape(Ersoy et al., 2022). However, although some research has been conducted in other industries, the pressure vessel industry has not been paid attention to. There is rarely systematic research on the circular economy actions of the pressure vessel industry or the relationship between information sharing and circularity. The pressure vessel industry is different from other industries since it’s rooted in the B2B market and the complicated value chain makes it even harder for stakeholders to communicate. Therefore, the study will become the first study gathering the existing current circular economy actions in the pressure vessels in mobility applications, with a particular focus on how inter-corporation information sharing could help with promoting circularity.

The study aims to investigate the current circular economy actions in pressure vessel industries, the external factors influencing the actions, and how inter-corporation information and knowledge exchange could promote the circularity actions. It aims to provide practical insights for stakeholders to use communication as a catalyst to make more circular actions. The research is intended to eventually help make the pressure vessel industry develop more circularly and prevent the environmental problems caused by the linear business model.

To achieve the research aim, the first research question is to discover what the current circularity actions in the pressure vessel industry and the external factors are influencing these actions, they will be categorized into politics, economics, society corporative norms, and technology. The second research question is to investigate the key actors in the circular actions and the information needs of each actor to facilitate circularity.

RQ1 What are the existing circular economy strategies in the pressure vessels in mobility application and why?

RQ2 What are the key action points and the information needed for the actors in the value chain to conduct such circular economy strategies?

1.3 Scope and delimitation

The geographic scope is Sweden, and the industry focus is the pressure vessels in the mobility application, especially the ones that are installed in vehicles as fuel storage tanks. All four pressure vessel types are included, but epically focus is on Type I and Type IV (Carbon-Fiber-Reinforced Plastics) because they are the most commonly used pressure vessel types on vehicles so far. All types of gas vehicles are included, for the CNG, LNG, and Biogas vehicles, the Type I pressure vessel is dominating while very limited Type IV can be found. For hydrogen fuel-cell vehicles which were introduced to the market very recently, the Type IV is expected to be the dominating type.

To answer RQ1, all the circularity actions are intended to be studied, including maintain, reusing, refurbishing, remanufacturing, and recycling. However, the research finds out that the reuse, recycle and eco-design actions are the dominating CE strategies regarding pressure vessels in mobility applications as far. Reuse is defined as "Repeated use of a product or component for its intended purpose without significant modification"(Ellen Macarthur Foundation, 2021). In this research, reuse action means the used pressure vessel is reused and reinstalled in another vehicle. Recycle is defined as "Transform a product or component into its basic materials or substances and reprocess them into new materials."(Ellen Macarthur Foundation, 2021). In this research, recycle action means that pressure vessels are sent to pressure vessel specialist recyclers, and the material such as carbon fibre from used pressure vessels is recycled and then applied in manufacturing new pressure vessels. Eco-design is defined as "The integration of environmental aspects into the product development process, by balancing ecological and economic requirements" (UNEP, 2001). Because reuse and recycling require the actions of reverse logistics, where the supply chain is dedicated to the reverse flow of the material, the actors in the downstream value chain are the research target group. They include vehicle dismantlers, vehicle workshops, and recyclers, all of whom are the direct actors involved in the reverse logistics process. The pressure vessel producers are the target group of the eco-design actions. Other stakeholders who could influence the actions of the key actors are also studied, they are 3rd party inspection companies, vehicle producers, and spare part trading platforms. To answer why such CE strategies have been taken so far, the external factors from legislation, economic and market, social and corporation norms, and technology are studied by using the PEST analysis framework.

For the RQ2, the study focus of this research is inter-organization information exchanging behavior, the organizations are the direct actors in the reuse, recycle, and eco-design actions. The assumption is that the actors make circular actions based on certain information, and the information demands and needs of every actor are different based on their actions. Organizations need to exchange information from the outside environment and other actors to satisfy their information needs. Although organizations process and utilize the information in different ways, which could hugely impact their action in the end, internal information utilization is not in the scope of my study.

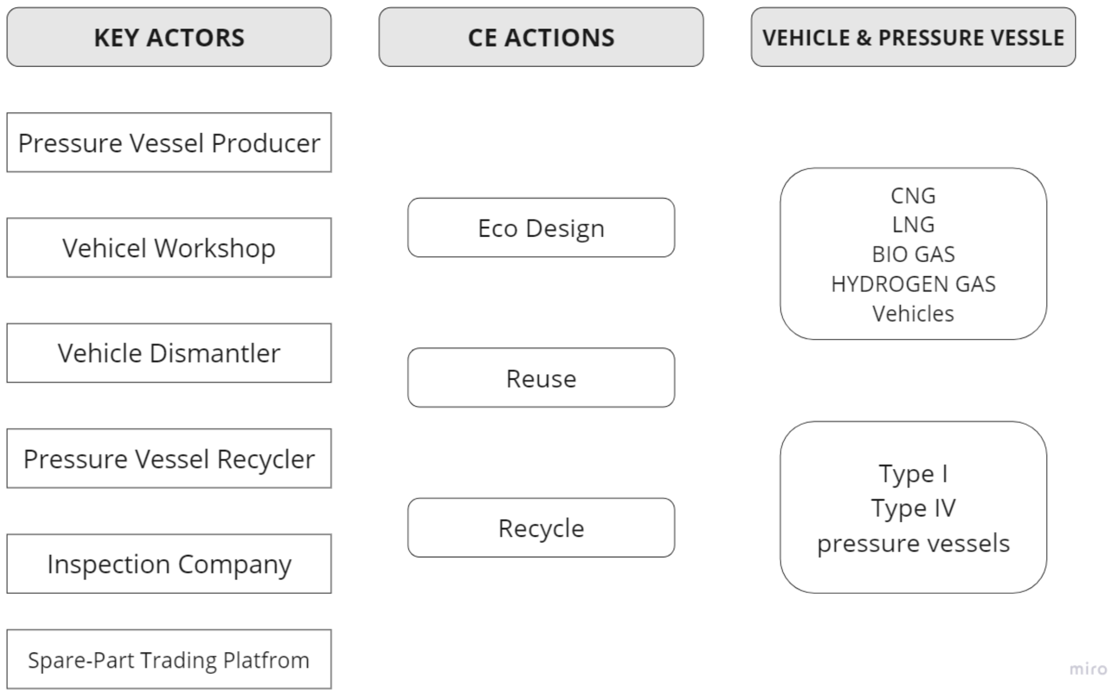

Figure 1-1 'Scope of the research design'

1.4 Ethical consideration

Since the targeted interviewed group is private corporations, disclosing any sensitive information about companies in the final report is one of the ethical considerations. The study prevents the leakage of any sensitive information in the process of collecting data as well as in writing. The information about the researcher's name, the department, the purpose of the interview and study, the topic and potential implication of the study, and who can have access to the study after it's finished was informed to the interviewees. All the data collected from interviewees is stored in USB flash drives and has not been disclosed to anyone. In the writing process, all the interviewees and the companies they work for have been anonymized, only the role of the companies is disclosed and coded. The interviewees are referred by the role of the companies they work in (i.e. Vehicle manufacture, vehicle workshop, vehicle dismantler).

1.5 The audience

The expected findings are the answers to my research questions and the answers will provide practical insights into what are the existing circular economy actions and show how can inter-corporation information sharing promote circularity in the pressure vessel industry in mobility applications. The outcome such as what kind of information is needed for advancing circularity, what knowledge exchange channel and form is more accessible, and how to improve the process in the future will provide practical inspiration and insights for all participants including manufacturers, users, service providers, and recyclers to improve circular performance. The outcome will help key actors in the pressure vessel value chain to picture the status quo of circular economy actions in the whole industry, and provide them with the knowledge of using information exchange as a catalyst for advancing circularity performance.

There is growing legislative pressure from the EU on information sharing and disclosing, such as the Sustainability Corporation Reporting Directive(DIRECTIVE (EU) 2022/2464, 2022), which puts stricter pressure and requirements on data disclosure on corporations and the Green Claim Directive(2023/0085 (COD), 2023), which requires corporations to disclose data if they intend to make green marketing claims. There is also an increasing demand for circularity in the mobility industry, a new proposal on the End-of-life Vehicle Directive (2023/0284 (COD), 2023) proposes stricter circularity requirements for vehicle design and management of end-of-life vehicles and suggests applying extended producer responsibility. With growing legislation pressure, the study could bring practical insights and suggestions on how to use inter-corporation information sharing as a catalyst to advance circularity in the pressure vessel industry in mobility applications, and eventually help the industry grow more circular.

Apart from the participants, academics will also be the audience of my research. The existing CE strategies in pressure vessels in mobility applications are systematically collected and the reasons are analyzed. Moreover, how information and knowledge sharing promote circularity has already been studied in many industries, but this study will be the first research that provides empirical insights into the pressure vessel industry in mobility applications. While many of the previous research focus on information sharing among the supply chain actors such as suppliers, manufacturers, and users. This research has a particular focus on the downstream actors, such as dismantlers, workshops, and recyclers, who play a crucial role in reverse logistics and closing the loop. Therefore, this study will also contribute to the study of information sharing in reverse logistics.

1.6 Disposition

Chapter One introduces the background of the topic and justification of the research topic. It includes the problem definition, the aim and research questions, the scope of the study, ethical considerations, and the potential applications of the results.

Chapter Two displays the literature review of the previous study in this field, including the relationship between information and circular economy, the current circular economy actions in composite, and the PEST analysis framework.

Chapter Three shows the research design and methodology of the study, including the method used to collect and analyze the data, and what types of data have been gained.

Chapter Four displays the main findings of the study, it includes the current circular economy actions in the pressure vessel industry in mobility application, the external factors, the critical action points, and the information needed.

Chapter Five discusses the reason why certain CE is more common than others, summarizes the critical types of information, and compares the findings to previous studies.

Chapter Six concludes the answers to the research questions and makes recommendations on how to facilitate information sharing to promote circular economy in pressure vessels in mobility applications.

2 Literature review

2.1 The pressure vessels in the mobility application and waste management

The main function of the pressure vessel is to hold fluids at a certain pressure substantially. Regarding their applications in mobility sectors, pressure vessels are usually used as fuel containers for CNG, LNG, Biogas, and Hydrogen gas. Based on their construction materials, there are four types of commercial pressure vessels (Type I, Type II, Type III, and Type IV). Type I is constructed fully of metal steel or aluminum, while Type II is mainly constructed with metal steel or aluminum as a liner with glass fibre composite wrapped in the hoop direction. Type III and Type IV are mainly made from Carbon Fiber Reinforced Plastics (CFRP). Type III has a metal liner and is fully wrapped with CFRP outside, and Type IV has a polymer liner, generally polyamide or high-density polyethylene, and is wrapped with CFRP outside. Type V is fully composite construction without any kind of linear, which has not been widely commercialized. (Das et al., 2016; Sloan, 2023)

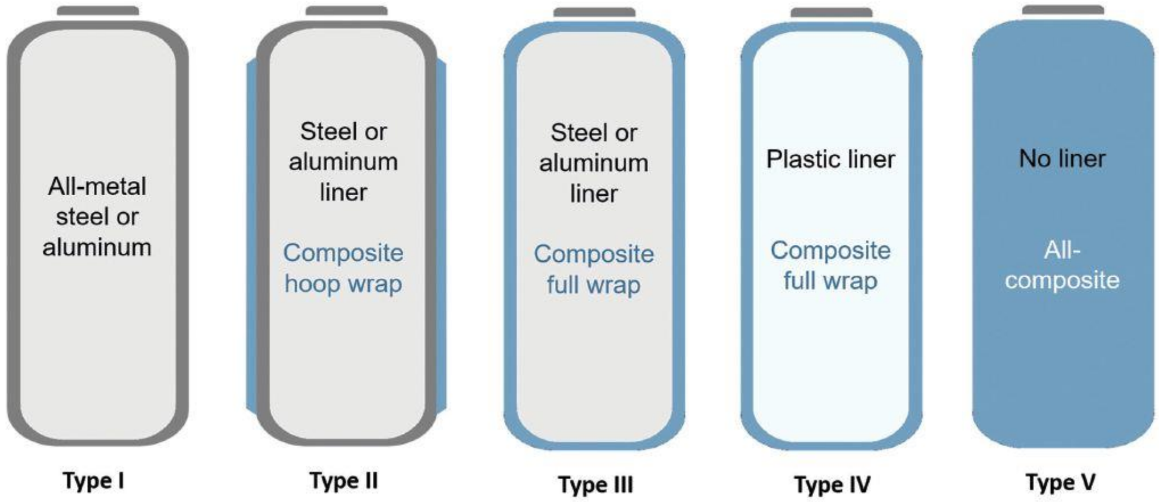

Figure 2-1 'Pressure vessel types and construction'

Source: "American Society of Mechanical Engineers (ASME) and the International Organization for Standardization (ISO)'

The Type I and Type II pressure vessels have price advantages but they are heavy and have lower operating pressures and service life. The Type III and Type IV pressure vessels are lightweight and have longer lifespans, while they have higher prices because of the highly expensive carbon fiber raw materials. Type I and Type II used to dominate the market, but with the demand for weight reduction and gas storage efficiency, Type III and Type IV pressure vessels are taking more market share now (Das et al., 2016; Sloan, 2023). The increasing demand for Type III and Type IV pressure vessels is mainly because of the increasing amount of hydrogen fuel cell vehicles (HFCV), which use hydrogen as the fuel. Nowadays, hydrogen is most efficiently stored as gas compressed in a range of 350-700 bar(Sloan, 2023), which is about 5,076–10,152 psi per pressure vessel. The high demand for pressure means the Type I and Type II pressure vessels can hardly fulfill the pressure requirement for the hydrogen vehicles.

Fiber-reinforced plastics are materials composed of fibres, resin matrix, additives, and fillers. Type IV pressure vessels are Carbon Fiber Reinforced Plastics (CFRP), and they are commonly chosen for hydrogen storage on hydrogen fuel cell vehicles due to their weight advantage and larger containing capacity. In Type IV pressure vessels, high-strength carbon fibre tows are "winded around the periphery of the liner in a helical and hoop direction to bear structural loads, while the liner prevents hydrogen leaks."(J. Zhang et al., 2023). The main materials of Type IV are High-density polyethylene (HDPE) inner, epoxy resins like thermosets or thermoplastics, and carbon fiber. Carbon fiber is the biggest cost of raw materials.

Compared to Type IV pressure vessels, Type I is much heavier weighted and has less operation pressure, but the price and carbon footprint of the raw materials are much lower. The Type IV pressure vessels have a lightweight and higher storage capacity advantage, however, the cost is much higher and the carbon footprint of the main raw material is almost 10 times (Kawajiri & Sakamoto, 2022) higher than the Type I pressure vessels. Table 2-1 below compares the key characteristics of Type I and Type IV pressure vessels.

Table 2-1 'Type of pressure vessel and their comparison'

	Type I	Type IV
Construction materials	Steel	Polymer liner and CFRP: HDPE, epoxy resins, carbon fiber
Weight (kilograms/ liter)	1.35	0.35
Maximum operation pressure (psi)	2900	10,000
The most valuable material	Steel	Carbon fiber
Cost of (USD / liter) in 2012	5 USD	16.25 USD.
The carbon footprint of main materials	The global average carbon footprint of crude steel production is around **1.91** tons of CO2 per ton of steel produced (World Steel Association., 2022).	The carbon footprint of 1 kg of carbon fibre is around **25** kg of Co2 eq emission (Kawajiri & Sakamoto, 2022)

Source: '(Sloan, 2023; World Steel Association., 2022)'

Carbon Fiber Reinforce Plastic (CFRP) shares about 5 % of the European composite market, however, only 2% of the composite materials are recycled in Europe (U.S Commercial Service, 2022) and most of them are landfilled or incinerated. This is mainly because of the technical challenge of recycling the fibres. With the CFRP increasingly applied to many industries including pressure vessels, the growing volume of EoL composite will be a huge concern. The production volume of CFRPs was approximately 52, 000 tons in 2021 (Colledani & Turri, 2022). The demand for CFRP is estimated to reach 285,000 tons and the waste during the manufacture and the end-of-life CFRP is expected to reach 20,000 tons per year by 2025. However, because of the lack of recycling techniques and the market, most of the carbon fibre is wasted in incineration and landfill.(J. Zhang et al., 2023).

2.2 The CE strategies on carbon fiber-reinforced plastics

The concept of circular economy has been developed since the 1970s, and it has been considered one of the most critical enablers and approaches for promoting sustainability. (Geissdoerfer et al., 2017) synergized different definitions of circular economy and identified it as "a regenerative system in which resource input and waste, emission and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." According to the waste hierarchy from the European Waste Framework (Directive 2008/98/EC, 2008), prevention, preparing for reuse, recycling, recovery, and disposal are options from most preferred to least preferred.

The circularity of carbon fiber-reinforced plastics composite is mainly discussed from the technical side, especially related to the recycling technology development. There are four recycling processes for the carbon fibre composite, they are mechanical, chemical, thermal, and fragmentation. The mechanical process breaks down the carbon fibre composite into tiny pieces and the scrap is used as implemented reinforcement material for other composites, which is not applicable for pressure vessels because the pressure vessels require endless carbon fibre. The thermal process through pyrolysis or oxidation is the most common method of recycling carbon fibre, where the carbon fibre composite is decomposed via a heating process, and short fluffy fibres are recycled in the end. However, the short fibre can't fulfill the length requirement of pressure vessels. The third treatment is chemical treatment via the solvolysis process to break down the resin and non-defective carbon fibre and 90% of the mechanical properties of the carbon fibre can be reserved in the process. However, the process is very high-cost and has a huge negative impact on the environment. The last method is the size-reduction method via fragmentation, which recovers the long and clean fibres(Isa et al., 2022; U.S Commercial Service, 2022).

Even though carbon recycling technology has been developed, the high-quality requirement of the pressure vessel for endless carbon fibre is still a technology challenge and only very few technology innovations have succeeded. Therefore, recycling the carbon fibre from an EoL pressure vessel and then applying the recycled carbon fibre in manufacturing new pressure vessels must handle the technology challenge of downcycling, which can be hardly solved. Some argue that market and financial factors will also influence the recycling of carbon fibre. Even though the downcycling challenge has been solved by innovation and the technology is capable of being scaled up, the challenge is about reducing the cost of recycled carbon fibre and developing the market. Without a business case and stable supply of EoL pressure vessels, no stakeholder is willing to adopt the new ecosystem because of the risk aversion of the supply chain(Francis, 2022).

Another circularity initiative related to the composite is cross-sectorial carbon fiber recycling (Colledani & Turri, 2022). The cross-sectorial circular approach is a proposal to recycle, reprocess, and reuse materials across different composite applications according to their quality requirements on carbon fiber. The carbon fiber from products in sectors "characterized by higher requirements and more demanding technical specifications will be recycled and reused in new products and applications featuring less demanding, more liberal specifications"(Colledani & Turri, 2022). According to the different quality demands of different composite applications, the requirement on the tense and strength of the carbon is different. The cross-sectorial recycling approach suggests that the carbon fiber from the higher quality requirement application could be recycled and reused on the application with lower quality requirements. Even though some material degradation is unavoidable in the recycling process, the material may still maintain sufficient residual quality property under quality control. According to the theory of the cross-sectorial circularity approach, the carbon fibre from the EoL of CFRP pressure vessel could be recycled, repurposed, and reused for applications such as wind energy, automobiles, sporting goods, and civil engineering. The supreme carbon fiber from aerospace could be reused and recycled on pressure vessels. To facilitate the cross-sectorial circularity, key stakeholders including material suppliers, logistical operators, technology providers, co-designers, and end users are needed(Colledani & Turri, 2022). Figure 2-2 shows the different requirements for carbon fiber quality from different applications.

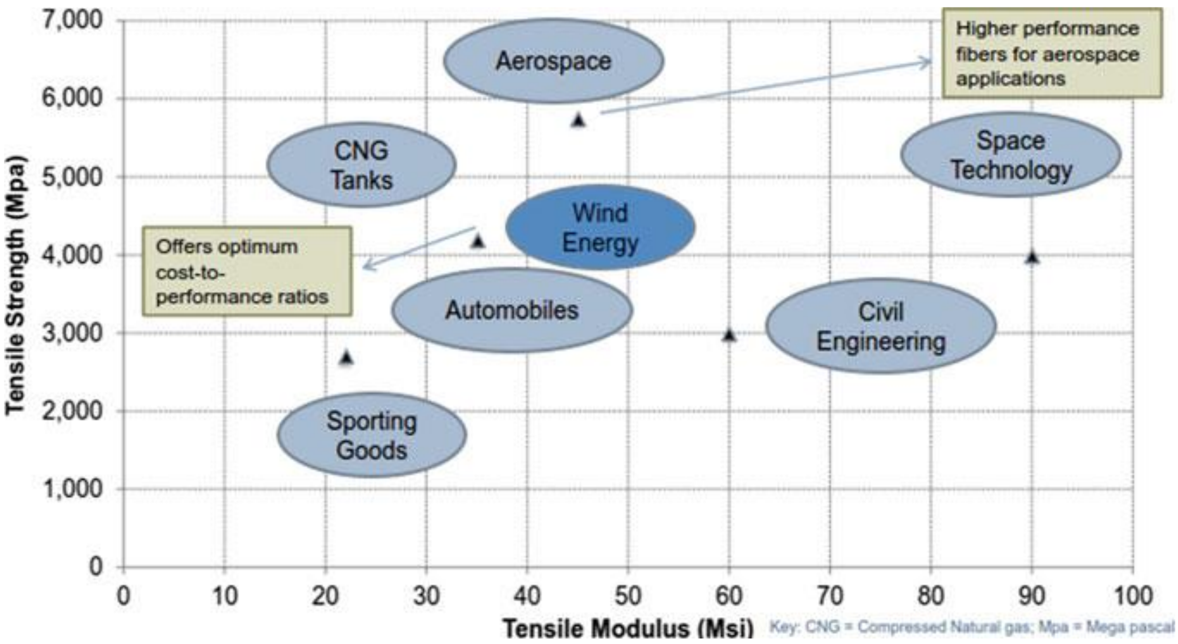

Figure 2-2 'Industry requirements for CFRP made parts in different sectors'

Source: '(Colledani & Turri, 2022)'

To conclude, there are currently two circular economy initiatives for Carbon Fiber Reinforced Plastics discussed in the academic, the first one is developing the recycling technology and trying to recycle the carbon fibre from EoL composite and then utilize the recycled carbon fiber for manufacturing new pressure vessels. This approach requires a technical solution to solve the downcycling challenge and a stable supply of the EoL CFRP. Another circular economy approach is cross-sectorial recycling, reprocessing, and reusing, which suggests that EoL carbon fiber from the higher quality demand application could be reused in other sectors with lower quality demand.

Even though there is research on the circularity actions of composite, carbon fiber reinforced plastic, and carbon fiber, there is no systematic research that exclusively focuses on the pressure vessel industry from academics. Therefore, this study will be the first research systematically exploring the existing circular economy actions on pressure vessels in mobility applications.

2.3 Theories relevant to information sharing and circularity

2.3.1 What has been studied related to information sharing and circularity

Information is considered a catalyst in promoting circularity since the information and data could hugely impact a corporation's decisions. While some of the information could be gained internally, corporations also need to receive information externally. The topic of information sharing and circularity has been studied in many fields, including both social science and natural science. According to a systematic literature review by (Jäger-Roschko & Petersen, 2022), there are at least four disciplines explored this topic. Operations research focuses on the economic impact of information-sharing in the circular economy, while environmental management focuses on the environmental impact. Computer science intends to provide practical solutions for information-sharing channels and platforms, and engineering explores solutions for storing and handling information.

Information exchange among actors could help promote circularity. Corporations can make proper circularity actions based on sufficient information and knowledge, while some of the knowledge could be obtained internally, corporations also rely on the information shared by other actors in the value chain. For example, manufacturers can design products more sustainable (Scruggs et al., 2016) and prevent overproduction (P. Zhang & Xiong, 2017) based on the feedback information shared from downstream actors. Service providers can improve the quality of maintenance service(Fargnoli et al., 2019) and make preventive maintenance based on the information shared by manufacturers and users(Metso et al., 2018). Recyclers can identify the valuable components more quickly and manage the waste more safely for workers based on the information shared by suppliers and manufacturers(Nowakowski, 2018). Generally, inter-corporate information sharing could help all the actors in the value chain foresee future changes in the market or policy landscape (Ersoy et al., 2022). Therefore, to study the information-sharing process, it's very crucial to map the activities of different stakeholders in the value chain and study the information flow and exchange among them.

Apart from promoting circularity for the whole value chain, information, and knowledge sharing could also bring financial benefits to the stakeholders. For example, for service providers, information about the utilization and history of the vehicle helps them reduce the cost of inspections and improve the speed and quality of service(Zuo et al., 2020). For manufacturers, market and regulatory information helps them foresee the market opportunities and risks and reduce uncertainty, potentially preventing overproduction and reducing costs (P. Zhang & Xiong, 2017). For the recyclers, the market information helps them identify and process the valuable components more quickly and brings them financial benefits(Zuo et al., 2020).

Finally, considering information sharing could hugely promote circularity, scholars also study how to improve the information-sharing process so that it could help with advancing circularity. The most frequently mentioned suggestion is to create bigger incentives for all actors to share information since certain actors like recyclers and remanufacturers rarely receive information (Andersen & Halse, 2023; Jäger-Roschko & Petersen, 2022; Kurilova-Palisaitiene et al., 2015). Making information flow more inclusive, understandable, accessible, and standardized is another suggestion, which usually needs the intervention of governments (Burger et al., 2018; Jäger-Roschko & Petersen, 2022; Jensen et al., 2023). One debate is about the role of technology and digitalization such as digital product passports. Some scholars argue the solution is to provide IT infrastructure and channels (Koppelaar et al., 2023). Others argue it's not enough to just provide channels, but to improve the capacity and accessibility of technology (Burger et al., 2018). The remaining argue that the solution is not about the technology at all, but increasing motivation and incentives for sharing information (Kurilova-Palisaitiene et al., 2015).

To summarize what has been studied in the area of circularity and information sharing, the motivations, information flow, information sharing channels, technology, barriers and challenges, and impact have been paid attention to (Jäger-Roschko & Petersen, 2022). The industries that have frequently been studied are agriculture, electronics, and construction. The actors in the whole life cycle value chain have been studied, but special attention is given to the remanufacturers and recyclers. In terms of what has not been paid attention to and how can my study contribute. The pressure vessel and composite industry has not been studied, and there isn't enough effort to cover all the key actors in the value chain.

2.3.2 Theoretical framework of the study

Regarding the theoretical framework of the study, the PEST is used as the theoretical framework for analyzing the external factors influencing the circular economy strategies in RQ1. In terms of RQ2, the critical type of information summarized by previous scholars is the main theoretic source.

To answer RQ1 regarding why certain CE strategies are conducted, PEST analysis is conducted to evaluate the external factors that influence the decisions of the actors. PEST analysis is an analytical framework to understand the systematic external influencing factors of actions (Christodoulou & Cullinane, 2019). Considering corporations' decisions are influenced by both the information they receive as well as the external factors including politics& regulation, economics, social, and technology, a PEST analysis framework is used.

To answer the RQ2 regarding the critical action points and the information needed, previous scholars have already discovered the type of information helpful in promoting circularity and different scholars give different categories. (Ferguson & Browne, 2001) summarize six groups of information that could help with improving reverse logistics based on the view of recyclers. The types of information include product-related information, location-related information, utilization-related information, legislative information, market information, and process information. (Jäger-Roschko & Petersen, 2022) classify information needed to improve circularity into two groups, they are supply chain information and technical information. Supply chain information includes demand, supply, costs, and lead time, which are usually shared among product manufacturers, retailers, remanufacturers, and recyclers. Product history or life cycle data of individual products is the most crucial technical information, which includes static information, location information, instructions for disassembly, material composition, and so on. The technical information is usually shared among remanufacturers, recyclers, maintenance providers, consumers, and product manufacturers. (Luoma et al., 2021) summarized four types of data crucial for circular business models, including customer behavior, product and service lifetime, system performance, and material flows. Regarding reuse and redistribution, the product lifetime is the prerequisite and the customers' behavior and preferences are crucial. The digital platform could play the role of marketplace. Other valuable data include status, use, condition, and locations. Regarding the recycling actions, the data on the material flows and waste stream are the most valuable and the data about the design and lifespan could help with identifying the recyclability (Luoma et al., 2021). The type of critical information summarized by previous scholars set a theoretical base for the RQ2, and the critical information is summarized in table 2-2 below.

Table 2-2 'Critical types of information summarized by previous studies'

The type of critical information need	Description	Reference
Product related information	Component location, component identification, disassembly methods	(Ferguson & Browne, 2001)
Location-related information	The specific location of the product and the quality	
Utilization related information	Service life, amount of usage times	
Legislative Information	Legislations focus on recycling	
Market information	Market information on used products' demand, price, and availability	

Process information	Storage information related to the availability, sales information related to the sale history of the parts	
Supply chain-related information	Demand, supply, costs, lead time, yield information	(Jäger-Roschko & Petersen, 2022)
Technical related information	Product history and life cycle data, data and serial number, location, availability, dissemble, product current condition, material composition, performance of the products	
Product lifetime	Product lifetime, data related to usage, status, location, condition, and operation	(Luoma et al., 2021)
Material flow	Waste stream and material flow	
Product design	The design of the products	

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3 Research design

3.1 Research design

The research questions of the study are:

RQ1 What are the existing circular economy strategies in the pressure vessels industry in mobility application and why?

RQ2 What are the key decision-making points and the data needs for the actors in the value chain to conduct such CE strategies?

The overall method of the study is qualitative. "Qualitative research is an approach to exploring and understanding the meaning individuals or groups ascribe to a social or human problem." (Creswell & Creswell, 2018). The research data is collected from interviews with open-ended questions, observation as well as documents. The data analysis process is text analysis and interpreted by theme and patterns, using the framework of information management and PEST, the analysis process is inductive. The research is also an emergent design, the initial research plan is not tightly fixed, and the research questions and data collection method have been shifted and changed in the data collection period.

The qualitative method is considered the most appropriate approach for this study. The first reason is the exploratory nature of the research due to the lack of adequate knowledge regarding the circularity and information needs of the pressure vessel in mobility applications. The circularity actions on the pressure vessels in mobility sectors have not been systematically researched and studied in academics. Most of the research on circularity related to pressure vessels is only about the composite, carbon fiber reinforced plastics and carbon fiber instead of focusing exclusively on the pressure vessel. Moreover, most of the research related to composite circularity focuses on the technology side of circular economy actions such as the development of circularity recycling technology while there is limited research perspective from the information management side. As the explorative research to exclusively collect the existing pressure vessel circularity economy actions as well as exploring the relation between circularity and information sharing in the pressure vessel industry, the qualitative method is the most suitable for exploring the relatively new topic.

The second reason for choosing the qualitative approach is because the study aims to gain participants' opinions and experiences instead of testifying theory. Interviews aim to explore and interpret the participants' experience, opinions, and views regarding the CE strategies, the reasons behind and the information needed. The qualitative approach helps with gaining deep insights into the complex social phonomime.

To improve the validity of the qualitative research, the triangulation method is used to get data from different sources. For example, several different interviews are conducted for the same type of actor, including five vehicle dismantlers, two vehicle workshops, three pressure vessel producers, and two recyclers. To answer the why part of the RQ1, both interviews and literature reviews are used for collecting and analyzing in PEST analysis on the external actors. Figure 3-1 shows the research design of this study.

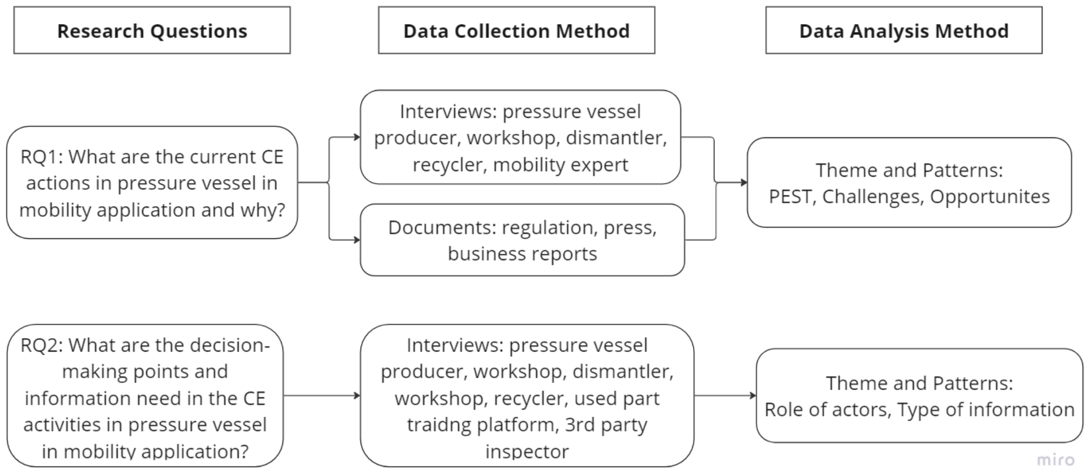

Figure 3-1'Research design'

3.2 Methods used to collect the data and Material collected

There are two data collection methods, including qualitative interviews and document literature review. Regarding the two research questions, the research is divided into two parts. For the RQ1, to collect the existing CE strategies for the pressure vessel industry, semi-structured interviews are conducted, the interviewees are the actors in the pressure vessel value chain who are the direct actors in performing CE strategies, with a particular focus on downstream actors such as pressure vessel producers, the vehicle workshop, dismantlers and recyclers as well as experts in vehicle ecosystem. To study the reasons why such CE strategies are adopted currently, a literature review, mainly the public documents such as reports, regulations, and news press is also conducted as complementary material apart from the interviews. For the RQ2, to collect the key action points and the data needed, the data is collected from the interviews with the actors in the value chain as well as other indirect but highly influencing actors in the ecosystem such as third-party inspection companies and spare part trading platforms.

3.2.1 Literature review

The function of the literature review in my study is three-holds. The first function is to search for previous academic studies related to the topic to justify the necessity of my research. The second function is to serve as materials and data in the data collection period to understand the external factors that influence the CE practices in RQ1. The final function is to serve as an analysis aid and explanation framework.

To achieve the goals, both academic and public documents such as regulations, reports, and media press were used. Regarding academic literature, the Google Scholar and Lund University search engine (LuBsearhch) is used and the keywords include “circularity”, “circular economy” “information”, “composite”, and “pressure vessels”, “mobility”. Regarding public documents and grey literature, they are mainly gained from online research portals while one of them is provided by interviewees. The first group of documents is regulations, including regulations such as Swedish regulations on gas vehicle inspection, pressure vessel lifespan limitation and data disclosure requirements, EU regulation regarding waste management, End-of-Life Vehicle Directive, Extended Producer Responsibility, and hydrogen economy roadmap. The second group of documents reports and press about the market and volume information of the gas vehicle, pressure vessels, CFRP composite as well as carbon fiber. The third group of documents are press and reports related to technology innovation and projects regarding carbon fiber recycling. Table 3-1 below summarizes the grey literature used in the study.

Table 3-1 'Summary of the grey literature review'

Title	Classification	Topic	Reference
Roadworthiness test of vehicles equipped with gas fuel systems	Regulation	Swedish inspection requirements on pressure vessels	Roadworthiness test of vehicles with gas fuel systems - Transportstyrelsen
Vehicle rules-Vehicles with gas tanks	Regulation	Swedish requirements on the limited lifespan of pressure vessels and data disclosure of date of service time	Vehicles with gas tanks - Transportstyrelsen
Statistics on vehicle gas	Press	Market and volume of Swedish gas vehicle market	Statistik om fordonsgas - Energigas Sverige
Passenger cars in traffic, new registration, total de-registrations and to abroad. Fuel gas, year 2014-2023	Report	Market and volume of Swedish gas vehicle market	Vehicle statistics (trafa.se) / *provided by the interviewees (ME)*
End-of-Life Vehicle Directive	Regulation	EU regulation on the waste management of vehicles	End-of-Life Vehicles - European Commission (europa.eu)
Ordinance (2023:132) on producer responsibility for cars	Regulation	Swedish Extended Producer Responsibility requirements on the vehicles	(Sveriges Riksdag, 2023)

3.2.2 Interview

The interview aims to collect direct opinions for the RQ1 and RQ2. The semi-structured interviews were conducted through online interviews and phone calls, and the structured surveys were conducted via email. The total number of the interviews is fifteen, seven of them were conducted via online meetings and phone calls, where semi-structured interviews with open-ended questions were asked. Five interviews were conducted with structured and open-ended questions. Three interviews are conducted on-site with semi-structured interviews and observation.

The interviewees are purposefully selected based on the circular economy strategy. To collect the existing CE practices (RQ1) and the information sharing flow (RQ2) in pressure vessels of mobility, the actors who are directly conducting the CE strategies are selected and interviewed. The key interviewees and actors are identified both by the author and the interviewees themselves. After the pilot research, the existing CE actions are identified as recycling and reusing, where the downstream actors are the key actors who are largely involved. According to the CE strategies and key stakeholders identified by (Ellen MacArthur Foundation, 2022), users, collectors, and service providers are the direct actors involved in the reuse action while users, collectors, and parts manufacturers are the direct actors in the recycling action. Therefore, the key actors such as pressure vessel producers, vehicle dismantlers, workshops, and recyclers were purposefully selected as interviewees. To understand the external factors and the reasons why certain CE strategies are chosen (RQ1), except interviewing the direct actors mentioned before, some highly influential stakeholders such as used spare part trading websites, mobility industry experts, and third-party inspection companies were also interviewed. The suitable interviewees were found and reached out by the author through the company web pages as well as snowballed by the interviewees. The interview guide was developed based on the literature review and adjusted dynamically depending on the role of the companies in the value chain. Notes were taken during the interviews and all the interviewees were anonymous by the author. Table 3-2 below summarizes the basic information about the interviewees.

Table 3-2 'Summary of the interviewees'

Type of actor	Topics	Form	Code
Vehicle dismantler	RQ1, RQ2	Online interview	VD1
Vehicle dismantler	RQ1, RQ2	Phone call	VD2
Vehicle dismantler	RQ1, RQ2	Email interview	VD3
Vehicle dismantler	RQ1, RQ2	Phone call	VD4
Vehicle dismantler (brand-own)	RQ1, RQ2	Online interview	VD5
CFRP Pressure vessel producer	RQ1, RQ2	Online interview	VP1
CFRP Pressure vessel producer	RQ1, RQ2	Email interview	VP2
CFRP Pressure Vessel Production Engineering Service Company	RQ1, RQ2	Email interview	VP3
Vehicle Workshop	RQ2	Onsite	VW1
Vehicle Workshop (brand-own)	RQ1, RQ2	Onsite	VW2
Recycler	RQ1, RQ2	Email interview	R1
CFRP Pressure vessel recycling technology innovator	RQ1, RQ2	Online interview	RT
Vehicle used spare part trading platform	RQ2	Email interview	TP
Mobility industry expert	RQ1	Online interview	ME
Third-party gas vehicle inspector	RQ2	Onsite	3I

3.3 Methods used to process data

For the RQ1 of the reasons and external factors influencing the existing CE actions, the data is coded based on the PEST framework, where the data is categorized into regulations & politics, economics & market, social & corporative norms, and technology factors. The PEST factors are also categorized into challenges and opportunities regarding the CFRP pressure vessels.

For the RQ2, the information is also coded by its type and function. The coding of the type of information is based on the expected codes from previous studies on the information and circularity. The previous research summarizes the useful information type into product-related information, location-related information, utilization-related information, legislative information, market information, and process information(Ferguson & Browne, 2001). Customer behavior, product and service time, system performance, and material flow (Luoma et al., 2021). Supply chain information and technical information(Jäger-Roschko & Petersen, 2022).

4 Findings and Analysis

4.1 The current circular economy strategies on Type I pressure vessel

4.1.1 The recycle action

The key action points

Recycling is the most common CE strategy on the Type I pressure vessel. After the gas vehicles reach the end of life, they are sold to vehicle dismantlers by individual vehicle users, dealers, and workshops. The car dismantlers disassemble the gas vehicles and take out the pressure vessels according to the safety requirements. The gas will then be emptied and drilled at both ends. Then the vehicle dismantlers sell the pressure vessels as scrap fractions to the recyclers for material recycling. The recyclers sell the recycled materials to potential buyers (R).

The key actors in the recycling process are the downstream actors including vehicle dismantlers and recyclers. The most critical decision maker is the vehicle dismantlers because their actions of taking out the pressure vessel from the vehicle make them the most direct and first owner of the used pressure vessel. Their decision to sell the pressure vessel as scrap fraction to a recycling company decides the CE action of the used pressure vessel is recycling, while they could also decide to resell it to potential actors for reuse, remanufacture, and repurpose. Therefore, their decisions are the most crucial and fundamental in terms of deciding which circularity action the pressure vessel will end up in.

The following section will discuss the key actions and decisions of actors in the value chain to make the recycling action happen. First, vehicle dismantlers receive End-of-life gas vehicles from individuals, workshops, and dealers, they are the material suppliers of pressure vessels. After vehicle dismantlers receive the used gas vehicles, they first identify the position of the pressure vessel on the vehicle, which is normally under the main body of the vehicle. The second step is to take pressure vessels out of the vehicle and then pipe out the gas if there is still gas in the pressure vessel, and this process is done with special equipment. The piped-out gas needs to be flamed due to the Swedish regulation for safety concerns. After the pressure vessel is empty, it will be opened, and the material composition of the pressure vessel can be identified easily. The dismantling process is more complex compared to the handling process of a diesel gas tank because it must follow certain safety requirements. After the pressure vessels are opened and the valves are removed, all of the pressure vessels are sold as scrap material to the downstream recycling company (VD1).

Among all the actions of vehicle dismantlers, the key action point is that the dismantlers decide to sell the used pressure vessel as the scrap fraction to the recyclers instead of considering them as reusable spare parts. One of the main reasons is that the dismantlers don't see any potential reusing market and customers or other applications for the used pressure vessel (VD1, VD2, VD3, R), therefore, selling them as scrap fraction to a recycler is the most common decision with limited transaction cost.

After dismantlers take out the used pressure vessels, recyclers purchase the pressure vessels as scrap and material recycling them, and then the material is sold as recycled material to potential buyers.

The information need on key actions

In this section, the information needs behind the key action points are shown, while some of the information can be gained internally, some of the data and information are received from external actors.

The first group of actors includes individual vehicle users, workshops, and dealers. They are the provider of EoL gas vehicles to dismantlers. Their main action is to sell the EoL gas vehicles to the dismantlers. To do so, they need market information about the potential dismantlers. This kind of market information is usually provided by the dismantlers (WS1) as well as the dealers' internal connection with certain brand-owned dismantlers (VD5).

The second key actor is the vehicle dismantlers. They are the provider of used pressure vessels for recyclers. For the first action of receiving the gas vehicle, they need market information on their upstream EoL gas vehicle providers, the information is provided by dismantlers' upstream EoL gas vehicle providers as well as their internal knowledge and connections. The second action is identifying the position of the pressure vessel on the gas vehicle, they are usually internal knowledge from the dismantlers' own experience and the dismantling manual from the vehicle producer is helpful. For the technical process of taking the pressure vessel out of vehicles, flaming the gas, and opening the valves, dismantlers have to follow the national regulations and requirements for safety concerns, and they are provided by the governance authority and dismantling manuals. The final step for the dismantler is to sell the pressure vessel as scrap fraction to the recycler, and they need market information about the value of the material as well as the downstream recyclers who will purchase the used pressure vessels. The market information is provided by the recyclers.

The final key actor is the recyclers, who are doing the material recycling of the used pressure vessel. Their first action is to purchase the used pressure vessel from dismantlers, where the market information about the dismantlers is needed. The second action is doing material recycling of the pressure vessel, where they need to follow the requirements of the recycling process and the knowledge about recycling. Regulation and technology information can be gained from governance authority as well as internal knowledge. The final action is to sell the recycled material to the potential buyers, and market information about the demand is needed and provided by the buyers. Figure 4-1 below summarizes the key actors, key action points, the information needs, and the source of the information. A detailed table can be found in the appendix.

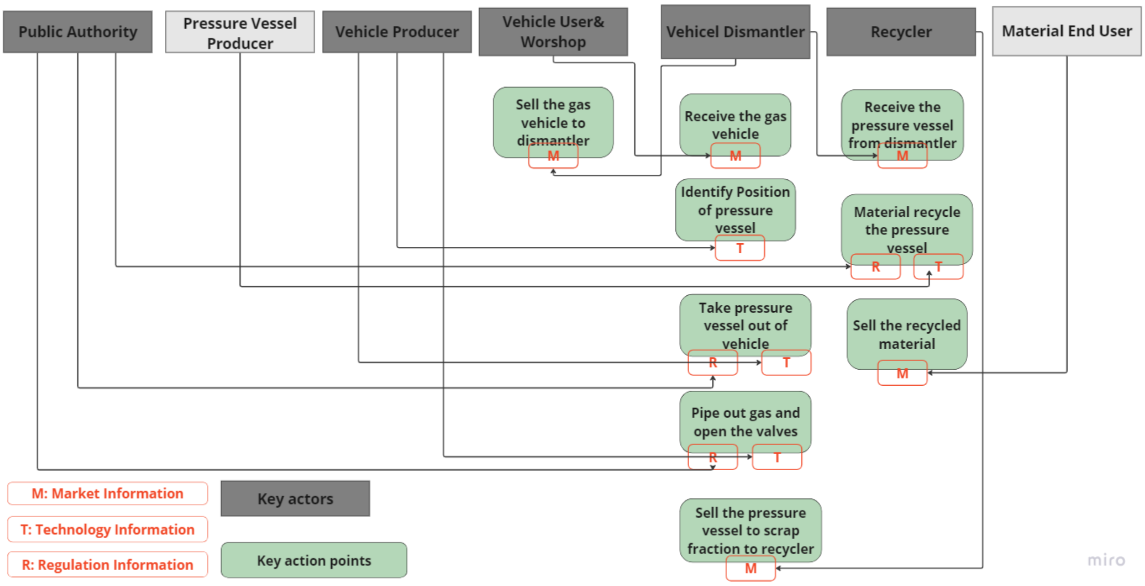

Figure 4-1 'Key actors, actions, information need and sources in the recycling action of Type I pressure vessels'

4.1.2 The reuse action

The key action points

While the most common CE actions on the Type I pressure vessels are recycling, reuse actions can also be discovered even though they are very rare. This section will discuss the actors involved in reuse actions, the key actions as well as the material flow in this process. The reuse action contains two key decision makers, the first one is the reuser, who are usually individual gas vehicle owners, and the workshop that installs the used pressure vessels. The demand for used pressure vessels is because some pressure vessels fail the annual inspection, and the gas vehicle owner is required to replace the failed pressure vessel with another pressure vessel. Some of the gas vehicle owners decide to purchase the used pressure vessel from an EoL gas vehicle from dismantlers. On the other hand, the dismantlers are the suppliers of the used pressure vessels because they are the most direct and first owners of the used pressure vessels. Their critical action is to sell the used pressure vessels as valuable spare parts to potential users instead of selling them as scraps to recyclers.

The material flow is as follows. After a gas vehicle reaches its end of life, they are sold by individual gas vehicle owners, workshops, and dealers to dismantlers. The dismantlers then disassemble the gas vehicle and take out the pressure vessel according to the safety regulations and dismantling manuals. Then the visual inspection is carried out by the dismantlers, the reusable pressure vessels are listed on the independent trading website or brand-own dealer networks as spare parts. The potential buyers then find the matching pressure vessels from the trading platform. Then the spare part will be delivered to the workshops and the workshop will inspect the quality of the used pressure vessels including doing the leakage test and then installing the spare part on the gas vehicle.

The dismantlers' key action is to sell used pressure vessels as spare parts. The dismantling process is the same as the recycling action, the dismantlers receive the End-of-Life gas vehicle and dismantle the gas vehicles, which includes taking out the pressure vessels, piping out and flaming the gas inside, and opening and cleaning the pressure vessels. Compared to dismantlers who sell used pressure vessels as scrap fractions, the dismantlers who sell them as spare parts have more actions to take. After the dismantling process, the dismantlers make a crucial decision to make a visual inspection of the pressure vessel by themselves to identify the reusability of the used pressure vessels. The dismantlers first decide whether the lifespan of the pressure vessel has already exceeded the regulation limitation. After that, they follow the inspection guidelines and requirements that the third-party inspection agency uses in the regular annual vehicle inspection to decide the reusability of the used pressure vessels. The inspection carried out by the dismantlers is visual inspection which mainly focuses on the damage level of the pressure vessel, but they could not conduct the leakage check since they lacked equipment. The pressure vessels that fulfill the visual inspection requirement are considered reusable and will be sold as spare parts and the ones that cannot pass the inspection are sold as scraps to recyclers. The inspection is the most crucial action in the process because it decides the reusability of the pressure vessels. Once the inspection is done, the pressure vessels that passed the inspection will be put on a reused part trading website or dealers' networking for selling. The technical information about the pressure vessel will be shown to the potential buyers to identify whether the pressure vessel matches their demand or not.

The potential buyers are usually the repairing workshop and individual gas vehicle owners, who collectively decide whether to purchase the spare parts provided by the dismantlers. Therefore, apart from the gas vehicle dismantlers who decide to sell the used pressure vessel as spare parts, the potential buyers also make the key decision of purchasing a used pressure vessel instead of a virgin one. Once the dismantlers' used pressure vessel matches the demand of the potential buyers, the used pressure vessel will be delivered, and a one-year guarantee is given to the buyers to eliminate the risks of failing the regular third-party inspection. The workshops will conduct a leakage check according to the inspection guidelines to ensure the reusability of the pressure vessels and then install the pressure vessel on the gas vehicle. Once the deal is made, the pressure vessels can be reused in the future (VD4).

The information needs on key actions

Compared to the recycling process, the reuse process requires the dismantlers to make more actions and decisions, including inspecting the lifespan and quality of the pressure vessels and then trading the pressure vessels with potential buyers. The potential buyers also must make actions and decisions including searching for spare parts and purchasing the used pressure vessels. In this section, the focus is on key actions that are not involved in the recycling actions and the information needed.

The first group of actors is the EoL gas vehicle provider, including the individual vehicle users, workshops, and dealers, who are the same actors in the recycling process. They sell the EoL gas vehicle to dismantlers, and the market information about the dismantlers is needed, which is usually provided by the vehicle dismantlers.

The second actor is the dismantlers, their actions include dismantling the gas vehicle, taking out the pressure vessels, inspecting the lifespan and quality of the pressure vessels, and then selling the pressure vessel as a spare part. Regarding the actions of receiving the gas vehicle, identifying the position of pressure vessels, taking pressure vessels out of the vehicle, piping out gas, and opening the valves, they are the same as the recycling process, and the next paragraph mainly focuses on the investigation and selling actions.

After the pressure vessels are taken out from the vehicle, the first inspection is on the lifespan. The Swedish regulation set a lifespan limitation on the pressure vessel, which is a maximum of 15 years before 2002 and a maximum of 20 years after 2002, the pressure vessels that exceed the lifespan limitation cannot be reused (Transport Styrelsen, 2024). Therefore, the first step of inspection is on the lifespan of the pressure vessel, and dismantlers need the lifespan information of the pressure vessels. Since the regulation also requires the pressure vessel producers to state the manufacturing date of the pressure vessels, the information on lifespan is provided by the pressure vessel producers and is mandatory by the regulation. The next inspection step is focused on the quality of the pressure vessels to decide their reusability. The inspection guidelines are the information needed in this action. The inspection guidelines are provided by the governance authority. The dismantlers use the same inspection guidelines that the third-party inspection agency uses in the annual inspection to decide the reusability of the spare part. What is worth mentioning here is that the dismantlers can only conduct the visual inspection of the pressure vessels, namely inspect whether there is certain damage on the surface such as rust, abrasion, damage or whether the gas tank has been pressed in some way. The dismantlers do not have the equipment for leakage checks, therefore the inspection of the leakage and whether the pressure vessels are properly attached to the vehicles are checked by the workshops after the pressure vessels are sold (VD4). The inspection requirements and guidelines are made by the Swedish government and can be accessed by the public. The information about the lifespan and inspection guidelines helps the dismantlers decide the reusability of the pressure vessels. The pressure vessels that pass the inspection will be sold through a spare part trading platform or dealer network platform, which provides the dismantlers the market information about the potential buyers.

The final key actor is the gas vehicle owner and workshop, who is the end user of the used pressure vessel, inspects the quality of the pressure vessels, and finally installs the used pressure vessel in the vehicle. Their first action is to find the dismantlers who are selling the used pressure vessel as spare parts, and the market information about the sellers is provided by the dealer network as well as the spare part trading platform. After the dismantlers are found, the next step is to match their demands with the pressure vessels that the dismantlers provide. They need quality information as well as identification information to decide whether their demand is matched. This kind of information is usually provided by the dismantlers, and the trading platform encourages the dismantlers to provide as much data as possible for buyers to identify whether their demand is matched, the information includes the article number and image of the vehicles (TP). After the product matches the demand of the vehicle users, the quality of the used pressure vessels will be checked again with a focus on the leakage check. The inspection process needs inspection requirements from the governance authority. The final step is to install the used pressure vessels in the vehicle, the quality of the pressure vessel will be double-checked and if the products do not match the demand of the customer, the pressure vessel will be returned to the dismantlers.

To sum up, in the reuse process, there are three key actors. Firstly, the vehicle users, workshops, and dealers provide the EoL gas vehicle to dismantlers. Secondly, the dismantlers take actions of dismantling, inspecting, and trading. The inspection of the pressure vessel is based on the lifespan limitation and inspection guidelines made by the Swedish government to decide the reusability of the pressure vessels, and the reusable pressure vessel will be traded via a used-part trading platform or brands-own dealers' network. Finally, the gas vehicle owner and workshop match their demand with the pressure vessel provided by dismantlers and then decide to purchase the used pressure vessel, double check and quality, and then install the pressure vessels in the vehicle. Figure 4-2 below shows the key actor, action points, data needs and sources in the reusing action of the Type I pressure vessel and a more detailed table can be found in the appendix.

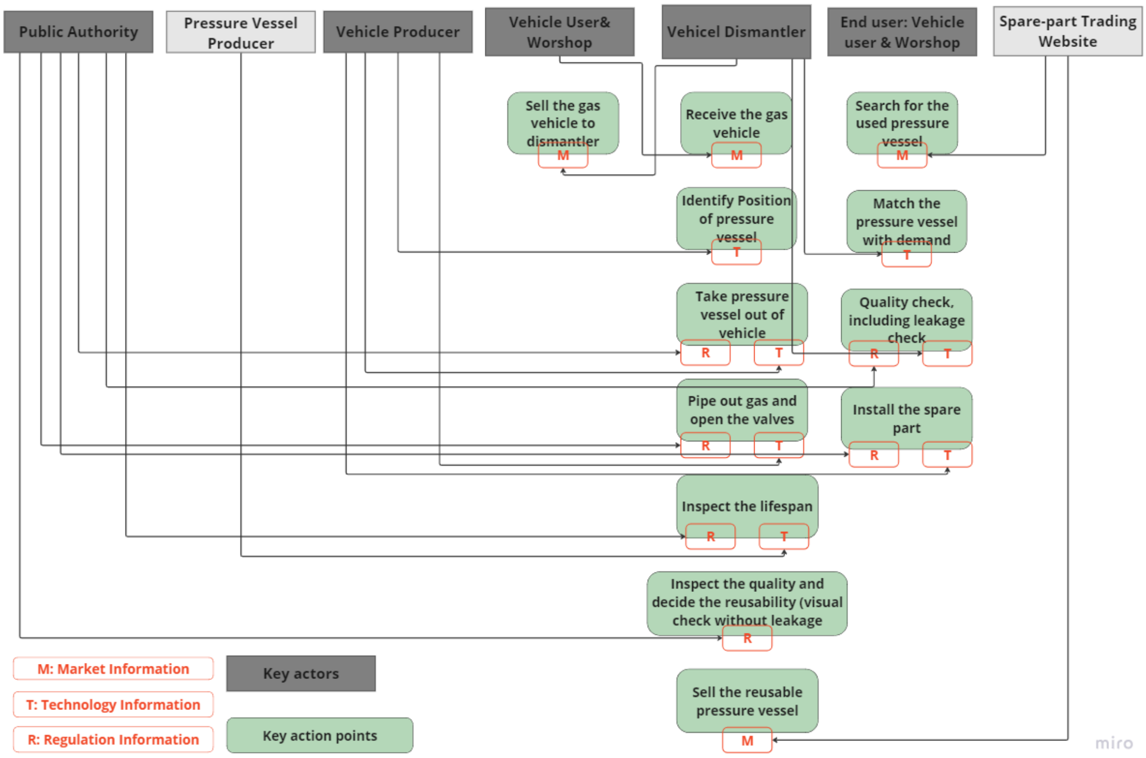

Figure 4-2 'Key actors, actions, information need and sources in the reusing action of Type I pressure vessel'

4.2 PEST analysis of the circular economy strategies

Regarding the Type I pressure vessel, recycling, and reuse are the commonly observed circular economy strategies while recycling is dominating. In this section, the PEST analysis is conducted to discuss how external factors including regulations, economics, society, and technology are influencing such circular economy actions.

4.2.1 Regulation

The regulations play a crucial role in deciding circular economy strategies especially because of the safety concern of pressure vessels. The existing regulation regarding pressure vessels includes the limitation on the lifespan and the requirement of inspection. These two regulations are double-edged swords, which both create opportunities and challenges for the circular actions on pressure vessels.

The first approach to minimize the safety risks is to regulate the lifespan of the pressure vessel. In the regulation by the Swedish transport agency, before 2002, pressure vessel producers could state the lifespan of the gas tank to a maximum of 15 years, and after 2002, the lifespan is a maximum of 20 years. Additionally, all the pressure vessels must be marked with an end-of-life date to indicate their lifespan by the pressure vessel producer (Transport Styrelsen, 2024). Once the pressure vessels reach the end-of-life date, they need to be dismantled from the gas vehicle. The users then have two options, the first is to change the pressure vessels, and the second is to switch off the gas operation and continue driving on the petrol.

This lifespan limitation creates opportunities on the demand side for the used pressure vessel if the car owners choose to replace the expired pressure vessel with a used pressure vessel spare part. The regulation requires that the manufacturing date of the pressure vessel must be stated on the pressure vessel, which also helps the dismantlers to identify the lifespan of the pressure vessel and then identify the reusability of the pressure vessel more efficiently. Once the dismantler notices the expiring date has not been reached, they could continue conducting the quality inspection on the reusability of the pressure vessel. Therefore, the information about the lifespan of the pressure vessel makes the reusability identification more efficient (VD2, VD3). However, even though the manufacturing date should be disclosed theoretically, some of the dismantlers claimed that they have not noticed the end-of-life date on the pressure vessel in reality (VD1), which makes it difficult to identify the reusability for dismantlers.

The second critical regulation is about the inspection. To avoid safety risks, the gas vehicles must undergo regular inspection, and the pressure vessels are the focus of the inspection. The inspection is mandatory for gas vehicle owners, the inspection needs to be done two times in the first five years and later every 14 months (3I). There are two ways for the users to inspect the pressure vessels. The first way is to inspect the vehicle at a third-party inspection company. The pressure vessels are supposed to be exposed in the inspection, and the inspection process includes checking if the tank is attached, if there is no leaking, and if there is no damage to the tank. The damage includes rust, abrasion, damage, or whether the gas tank has been pressed in some way (Transport Styrelsen, 2022). The second way is to show a certification (not older than 15 months) that indicates the pressure vessels and the rest of the fuel system work as they should. This kind of certification can be issued by the vehicle manufacturers or their representatives such as their workshops, or companies that have activities in post-conversion or repair or control of fuel systems for gas. The certification should not only include the results of inspections like visual inspection, function check, and leak test but also contain information like the name of the inspection workshop, data on issues of the certification and so on. The main job of the inspection is to identify whether the tank is functioning or not and to check the potential safety risks (WS2). All the inspection is required during the usage phase of the pressure vessel.

The inspection regulation creates a potential market for the used pressure vessels. The gas vehicle owners who fail the pressure vessel inspection are the potential buyers for the used pressure vessel. The most common reason for failing the inspection is because of the rust on the paintings, which is due to a low quality manufactured by the pressure vessel producers (VD4, WS2). Once the rust is identified, the pressure vessel must be replaced, which creates a market demand for the used pressure vessels as spare parts. However, on the other hand, this inspection regulation also limits the volume of reusable pressure vessels. The dismantlers use the inspection guidelines to identify the reusability of the used pressure vessels. Since the inspection requirements are very strict due to safety concerns, most of the used pressure vessels cannot be reused because they cannot fulfill the annual inspection requirements even if they are reused into another vehicle. Since the painting of gas tanks is usually in bad quality, rust is the main fault found on the gas tank, about 80% of the used pressure vessels dismantled from the used gas vehicle cannot be reused and only 20% of pressure vessels are reusable and will be potentially sold (VD4). Some dismantlers also claim that the extremely strict requirement on pressure vessels, especially about the rust concern hugely limits the reusability of the pressure vessels (VD1). The dismantler considers the rusted concern should not be considered as a reason for forbidding continuous usage because the rust is very normal and could be easily fixed by sandpaper (VD4). However, the strict quality requirement of the pressure vessel makes the reusability of the used pressure vessel nearly impossible.

The positive side of the inspection regulation is that it makes it convenient for the dismantlers to decide the reusability of the used pressure vessels. The inspection requirement provides the technical guidelines for dismantlers to identify the reusability and decide whether to resell the used pressure vessels as spare parts or not, and this kind of information can be easily accessed by the dismantlers from public authority. Therefore, even without the utilization information provided by the users, dismantlers can still decide the reusability based on the inspection requirements.

To sum up, the regulations on the pressure vessels are a double-edged sword for circular actions. The regulation of the lifespan creates a potential market for the reuse of pressure vessels, and the requirement of disclosing the manufacturing date of the pressure vessel helps the dismantlers decide the reusability of the pressure vessels. The inspection requirements create the demand for the used pressure vessels and provide guidelines for dismantlers to identify the reusability of the pressure vessels. However, the strict requirements also limit the volume and availability of reusable pressure vessels.

4.2.2 Economics

The economic and market factors influence the circular economy strategies, especially influencing the decision of the vehicle dismantlers to resell used pressure vessels as spare parts or scrap. The first external economic factor is the low market volume of pressure vessels, which makes the supply of used pressure vessels very limited and unstable. Most vehicle dismantlers (VD1, VD2, VD3) mention that among all the End-of-Life vehicles they received, a maximum of 10% of the vehicles are gas vehicles, and most of them are CNG vehicles with a few of them being biogas vehicles. The volume of used pressure vessel dismantlers received annually is usually only one to three. Such a low and unstable volume of the gas vehicle and the pressure vessel makes selling the pressure vessels as scrap the easiest and most convenient decision for dismantlers.

The overall volume of the gas vehicle is very low in Sweden. According to data from Energigas Sverige, at the end of 2022, the total number of gas vehicles is 51,194 in Sweden, and most of them are passenger vehicles and the volume has been decreasing since 2017 (Energigas Sverige, 2023). The low and decreasing volume of gas vehicles in Sweden means that the demand for used pressure vessels is very small and the market is decreasing too. Because of the limited and decreasing demand, dismantlers don't see any potential markets and value for selling the used pressure vessels as spare parts. VD1 mentioned that they noticed that some used pressure vessels could be repurposed in gas production in India and Africa in Agriculture, but no domestic demand or market for the used pressure vessels was identified by them, and that's the main reason why they sold the pressure vessels as scrap. Additionally, even though there is a demand for the used pressure vessel, most of the dismantlers have not noticed and recognized the domestic market (VD1, VD2, VD3), and the channel for the dismantlers to recognize the market information is limited. Therefore, the unawareness of the potential reusing market is one of the main reasons that most dismantlers choose to sell pressure vessels as scraps to recycling companies instead of as spare parts to potential reusers. VD3 also mentioned that they assume the gas vehicle is phasing out of the market, and they don't assume that there will be a potential buyer for the pressure vessels in the future, therefore, they decide not to resell the pressure vessels. The small and decreasing market of gas vehicles means the demand market for the used pressure vessels is very limited. The volume of gas vehicles in Sweden from 2004 to 2022 is shown in figure 4-3 below.

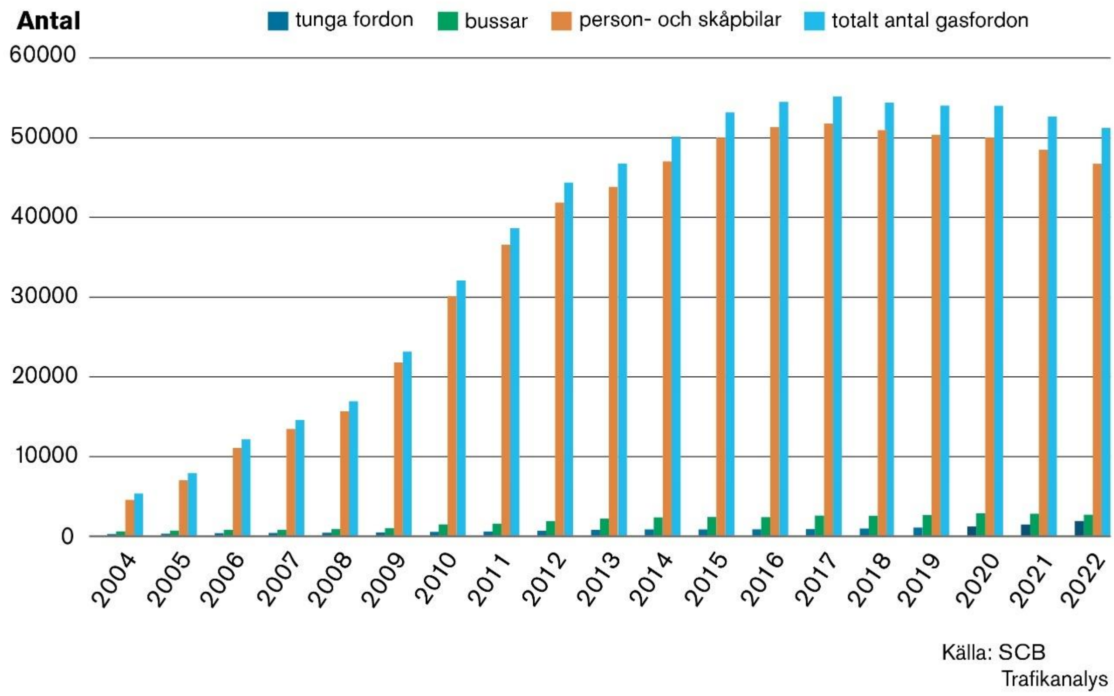

Figure 4-3 'Volume of gas vehicles in Sweden from 2004 to 2022'

Source: 'Energigas Sverige'

Moreover, the volume of End-of-Life gas vehicles is also very low, which means the supply of the used pressure vessel is not stable and high enough for reuse. Considering the life span of the gas vehicle and pressure vessel is about 15 to 20 years, the volume of gas vehicles before 2010 is very limited, which means most of the gas vehicles are still in the use phase. Table 4-1 below shows that the volume of deregistered passenger gas vehicles is 2784 in 2023, while 70% of them were exported, the actual volume of domestic End-of-Life gas vehicles is only 824 in 2023. It means that only around 800 End-of-Life gas vehicles were dismantled in Sweden and such a low and unstable EoL gas vehicle volume means the supply of the used pressure vessel is limited and unstable. Selling the used pressure vessels as spare parts brings extra work and expense for the dismantlers. Such a low number of EoL gas vehicles means that the circularity of the pressure vessels is not a concern and selling them as scrap is the easiest and most convenient way for dismantlers.

The small volume of EoL gas vehicles also makes it harder for potential buyers to find matching pressure vessels because the chances are very low. Among all the EoL gas vehicles, only 20% of pressure vessels can fulfill the inspection requirements and are available for reuse. Considering most of the dismantlers never sell the used pressure vessel as reusable spare parts, the chances for the potential buyers to find a matching pressure vessel are extremely low. In this sense, the transaction cost of making a deal is too high and it's much easier for customers to order a new pressure vessel instead of buying the used spare part (ME, WS2).

Table 4-1 'Volume of passenger gas vehicles in Sweden from 2014 to 2023'

Personbilar i trafik, nyregistreringar, avregistreringar totalt samt till utlandet. Drivmedel gas. År 2014–2023.

År	I trafik	Nyregisteringar	Avregistreringar	Varav avregistrering till utland	Nettoförändring
2014	40 095	5 021	1 609	1 185	2 767
2015	42 675	5 119	2 139	1 560	2 580
2016	43 693	3 810	2 076	1 423	1 018
2017	43 706	3 971	3 337	2 604	13
2018	42 463	3 288	4 095	3 341	-1 243
2019	41 633	4 971	4 621	3 808	-830
2020	41 047	3 525	3 910	3 081	-586
2021	39 542	1 548	3 208	2 357	-1 505
2022	38 086	1 919	2 682	1 844	-1 456
2023	36 528	2 034	2 784	1 960	-1 558

Source: 'Trafa.se / ME'

Apart from the low and decreasing volume of End-of-Life pressure vessels makes both the demand and supply of used pressure vessels very limited, reuse is not financially feasible than recycling for dismantlers. Reselling the pressure vessel as spare parts to potential buyers contains an extra cost which is not needed for selling them as scrap to the recycling companies because more actions are involved in the reusing actions than the recycling actions. The cost includes the cost of inspecting the reusability of the pressure vessel, the administration fee for reusing the pressure vessel, the transaction fee for seizing the potential buyers, the transportation cost from the dismantlers to the buyers, and the risks of not finding a matching buyer. The cost of inspection is especially considered as a huge financial burden for the dismantlers to carry (VD2). The extra costs and transaction costs will be a burden for both the dismantlers and the buyers. Both the end users and dismantlers do not think it's economically feasible for the buyers to buy a used pressure vessel rather than buying a new one and it's also a lot of extra work for dismantlers to bear (VD1, WS2). The higher cost of reusing actions than recycling is one of the main reasons the dismantlers choose to sell the pressure vessels as scrap instead of spare parts.

To sum up, the low and decreasing volume of the End-of-Life gas vehicles and pressure vessels makes both the demand and supply side for reusing the used pressure vessels very limited. Most of the dismantlers do not recognize the market demand for the used pressure vessels, it also adds extra work, cost, and risks because of inspection, storage, transaction and not finding buyers.

4.2.3 Social and corporative norms

The social and corporative norms also influence the CE strategies. One of the biggest social norms regarding the used pressure vessels is safety concerns. Both the supply and demand side are concerned about the safety risks of the used pressure vessels. Due to the safety risks of the pressure vessel, workshop, and gas vehicle owners tend to choose the new and safer pressure vessels instead of the used spare parts when there is a need to replace the pressure vessels (WS2). Reputation is a crucial concern the workshops of the vehicle manufacturers care about, and using the spare parts may create safety and reputation risks for them. Therefore, there is a tendency to choose a new pressure vessel instead of the used spare part (ME).

From the perspective of the dismantlers, selling the used pressure vessels means that they must carry out the inspection of the reusability of the pressure vessels themselves and look for potential buyers. However, most of the dismantlers do not identify the potential markets for used pressure vessels and do not have the knowledge and information about conducting the inspections. Moreover, most dismantlers have long-term corporations with recycling companies and it's a corporative norm for them to sell the pressure vessels as scrap instead of searching for potential buyers themselves (VD1, VD2, VD3).

4.2.4 Technology

Although a lot of safety concerns are coming from both regulation and users, the durability of the pressure vessels is not long enough for reuse. Mobility expert (ME) notices that there are a lot of problems with the pressure vessels, and they are not made as durable as wished. Many producers are trying to give up the gas vehicle and switch to normal combustion engine vehicles. The durability problem of the pressure vessels is also found by the dismantlers. VD4 notices that the painting of the pressure vessel is usually of bad quality, which makes the rusted problems very common. Once rust is found on the pressure vessels, they do not fulfill the inspection requirement and therefore cannot be reused (WS2).

To summarize the external factors influencing the circular economy strategies. In terms of opportunities, the opportunities are that lifespan limitation and strict inspection requirements create the demand for used pressure vessels, the requirements of on the disclosure of the lifespan and inspection requirements makes it easier for dismantlers to decide the reusability of pressure vessels. In terms of challenges, the low volume of domestic EoL gas vehicles and pressure vessels makes the supply of reusable pressure vessels very low, the low material value and high transaction costs don't create financial incentives for dismantlers. There is also a safety concern about reusing the pressure vessels from the end-user side, and the dismantlers rarely receive the market information of the potential end users. Finally, the low quality of pressure vessels makes them not durable enough for reuse. Figure 4-4 below shows the PEST analysis of the circular economy strategies regarding the Type I pressure vessels.

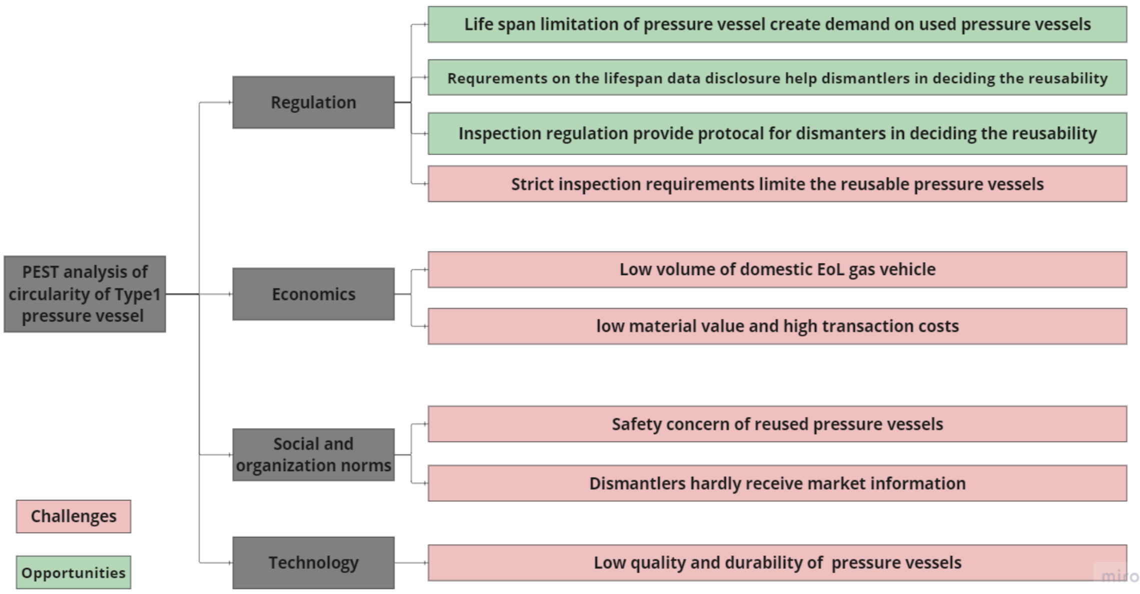

Figure 4-4 'PEST analysis of the challenges of recycling the Type I pressure vessels'

4.3 The current CE strategies of Type IV CFRP pressure vessels

Type IV Carbon-fiber-reinforce plastics (CFRP) pressure vessels have the advantage of being lightweight and have a large storage capacity for high pressure. Because of this, they are mainly applied for Hydrogen fuel cell vehicles while few for CNG vehicles. The current waste management of Type IV CFRP pressure vessels are landfilled or incinerated, which means the valuable materials such as carbon fibre in the pressure vessels are not regained and reused (VP3). Some dismantlers are currently stockpiling the used pressure vessels and waiting for the solutions to come up to regain the value of the materials (RT). Some CE initiatives are going on and they are mainly the eco-design from the pressure vessel producers and the recycling innovation of the pressure vessels.

4.3.1 Eco-Design

Key action points

The Type IV CFRP pressure vessels for vehicles have not been massively produced since hydrogen vehicles were just introduced to the market. Therefore, the volume of End-of-Life CFRP pressure vessels is very low. However, there are some CE initiatives carried out mainly by pressure vessel producers, with the aim of Eco designing the pressure vessel more circularly. The Eco-design initiatives include purchasing recyclable and recycled materials and designing the pressure vessel in an easily recycled way.

The first eco-design initiative is to purchase and use recyclable and recycled materials. Regarding the main material carbon fiber, pressure vessel producers are trying to purchase recycled carbon fiber and actively looking for recycled carbon fiber providers (VP1). Regarding other materials like resin, they are trying to purchase resins that are designed more recyclable or could be easily recycled such as self-degrading resins (VP1, VP3). Therefore, recycling the resin will be easier when the pressure vessels get recycled in the end.

The second eco-design initiative is to design the pressure vessel in a way so that recycling the materials is possible and easier after the end of life. Regarding carbon fiber, pressure vessel producers wind the carbon fiber in a certain way so that it is easier to rewind and recycle the carbon fiber after the end of life (VP2). Another approach is to reduce the complexity of the materials so that recycling will be easier. They are also trying to reduce the materials used in the product and minimize the number of different materials used in the pressure vessel to make it easier for dissembling and recycling after the end of life (VP2).

To sum up, regarding the eco-design initiatives for the Type IV Carbon-fiber-reinforce plastics (CFRP) pressure vessels, the key actor is the pressure vessel producers. Their key actions include purchasing recycled and recyclable materials as well as designing the product in a dissemble easily way.

The Information needs on key actions

According to CE initiatives mentioned above, the pressure vessel producers require data and information, while some of the data such as technology information could be gained internally, some data such as market information needs to be obtained externally.

Regarding the first initiative of purchasing recycled and recyclable materials including carbon fiber and resins. The first action for the pressure vessel producer is to search for suppliers (VP1), and the market information of potential suppliers is the information needed. This kind of market information could be provided by the supplier as well as the 3rd party information-sharing platform and trading platform. Since most carbon fiber recycling technology is under development so far and the market is still in the development stage, it's very hard to pressure vessel producers to find suppliers. After the supplier of recyclable and recycled materials is found, the second action is to purchase the recycled and recyclable materials. The cost and quality are the two key pieces of information that influence the decision to purchase. The cost of the recycled materials, especially the recycled carbon fiber must be cheaper than the virgin carbon fibers (VP1). Secondly, the quality of the recycled carbon fiber must be the same as the virgin carbon fiber. The tension and strength of the recycled carbon fiber must achieve certain criteria to be used in pressure vessel manufacturing, which is considered the highest quality demand for carbon fiber. Compared with purchasing virgin carbon fiber whose quality is undoubted, the quality of the recycled carbon fiber must be ensured and go under control to fulfill the quality requirements, and such quality data must be provided in detail by the recycled carbon fiber suppliers (VP1).

The second eco-design initiative is designing pressure vessels in a recycle-friendly way, including reducing complexity and wind carbon fiber in a more easily disassembled way. Pressure vessel producers need to be equipped with technological knowledge to reduce material complexity; this kind of technological information is mainly gained internally. Such knowledge could also be learned from other pressure vessel producers and other composite industries such as wind turbine producers (VP2). For winding and designing the carbon fiber in a more disassembled easily way, they require technological information about the design process. This kind of information is mainly gained internally but they also need to co-design the product with carbon fiber recyclers. VP2 is co-designing the product together with the carbon fiber recycling technology developer to make the product easier to recycle after the end of life.

To conclude, to purchase recycled and recyclable materials, pressure vessel producers need to search the suppliers based on market information provided by the suppliers, 3rd party information platforms, and trading platforms. The quality and cost data which is provided by suppliers are crucial for pressure vessel producers to decide whether to purchase recycled carbon fiber or not. To reduce the material complexity and wind the carbon fiber in a more disassemble-friendly way, technical information is needed. While most of the technical information is from internal knowledge, the pressure vessel producers also gain knowledge from other composite producers and co-design with carbon fiber recycling technology developers.

4.3.2 Material Recycling Innovation

Another circular initiative going on is recycling and recovering the carbon fiber from the End-of-Life pressure vessels and then reusing the carbon fiber in manufacturing new pressure vessels. The difficulty of this initiative is that the quality requirement of carbon fiber for the pressure vessels is very high and only continuous carbon fiber can be used for manufacturing pressure vessels. It has been a technical challenge to recycle continuous carbon fiber while most of the existing carbon fiber recycling technology cannot avoid the downcycling challenge.

There are a lot of initiatives and innovation projects going on for recycling the continuous carbon fiber from pressure vessels. In 2022, a technological innovation of recycling the continuous carbon fiber in the pressure vessels has been developed, the technical innovation has almost reached the end phase of development and is ready to be commercialized (RT). The recycled continuous carbon fiber could be used both in producing a new pressure vessel and for other applications in other composites.

In this initiative, the main actors are pressure vessel producers, carbon fiber recyclers, and vehicle dismantlers. The pressure vessel producers are responsible for designing and winding the carbon fiber in a way that makes it easy for the carbon fiber to be recycled as well as the end user of the recycled carbon fiber. The second actor is the carbon fiber recycler, whose job includes collecting the EoL pressure vessel, recycling the carbon fiber, and then selling it to end users. However, even though the recycling technology innovation developer is proving their innovation and trying to find recyclers who will commercialize their innovation, there are still no existing carbon fiber recyclers for CFRP pressure vessels on the market so far(RT). Some pressure vessel producers are considering doing the recycling process themselves (VP2). RT suggested that a specialist pressure vessel carbon fiber recycler should bear the responsibility instead of the pressure vessel producers because recycling the pressure vessel is a different business model for pressure vessel producers. The third actor is the vehicle dismantlers whose job is to collect the End-of-life pressure vessels and provide material feedstock to the recyclers. With the expected growing volume and the high residual value of the CFRP pressure vessels, the dismantlers desperately need a solution for handling the stockpiled pressure vessels (RT). The growing market also puts pressure on the vehicle dismantler, they need someone downstream to receive and recycle the pressure vessels.

However, the material flow and key actions of recycling the carbon fiber and then using it in manufacturing new pressure vessels are just assumptions. Even though the recycling technology has already been in place, the recycling market is still in the forming stage and there is no business case to back up the feasibility so far. The reasons include that the recycling innovation has not been widely noticed as well as the volume of End-of-Life pressure vessels is too small. Therefore, the recycling technology provider is the most active actor in this initiative so far, who is advocating for developing a recycling market (RT).

The recycling technology provider is aiming to commercialize, scale up production, and look for investment since the technology innovation for recycling the materials in the pressure vessels is approaching the end of the development stage. The biggest difficulty in this process is developing the recycling market and it's hard to find the right customer. The recycling technology provider is commercializing their innovation by campaigning to attract potential customers and showcasing the technological ability to recycle materials, especially advertising that the recycling technology of recycling continuous carbon fiber without downcycling has already been developed. They are also trying to highlight and prove the value of recycled continuous carbon fiber is profitable enough and that it's a financially feasible business (RT).

4.4 The Challenges of the Circular Economy Strategies

The main circular initiatives regarding the Type IV CFRP pressure vessels are that pressure vessel producers are eco-designing the pressure vessels by using recycled and recyclable materials such as carbon fiber and resins, and the recycling technology developer is developing the recycling market. However, there are a lot of external challenges to achieving the CE strategies, which could be analyzed by the PEST framework.

4.4.1 Regulation

The biggest regulation challenge is the unclear End-of-Life treatment regulation on the composite and pressure vessels. The EoL composite is normally not systematically collected and prioritized on the regulation consideration. The estimated amount of EoL volume of the pressure vessel as well as the waste treatment is very rare. The European Waste Directive(Directive 2008/98/EC, 2008) does not set specific requirements on the composite while only a few countries have specific regulations on composite. The Netherlands LAP3 waste management indicates that the minimum standard is reuse and recycle for thermoplastics and thermal recycling for thermosets, landfill is not acceptable. In Finland, composite is exempted from the landfill ban while most of the composite waste is processed by incineration(Colledani & Turri, 2022). However, there are no specific requirements on the treatment of composite or landfill ban on composite in Sweden. In European countries that don't have landfill bans, landfilling is the dominating waste treatment process for composites because it's the cheapest option (Colledani & Turri, 2022).

There is also no direct circularity requirement on composite and the lack of mandatory requirements on the circular aspect of composite leads to the unclarity of responsibility and the lack of incentive and motivation for actors to act. VP3 mentions that without mandatory requirements on the circularity such as how much percentage of materials are required to be recycled, no actors in the supply chain will be eager to invest in the circular design. VP3 suggests that the number of materials to be recycled or reused should be required and the requirement also needs to be tightened with time.

4.4.2 Economics

The second challenge is the unknown costs and quality of recycled carbon fiber. The decision to purchase recycled carbon fiber is based on the requisition that the cost of the recycled carbon fiber must be lower than the raw materials (VP1). However, since there is no recycled endless carbon fiber on the market, the cost for the pressure vessel producer is unknown and it's hard for them to decide to purchase the recycled carbon without any information about the price. Another concern related to the cost is that there is a risk in the quality of the endless carbon fiber. The information about the quality of virgin endless carbon fiber is known and exact for the pressure vessel producers while the quality of recycled endless carbon fiber is unknown and sheds potential risks on using them. The quality of the recycled endless carbon fiber depends on many factors such as the quality of the virgin fiber, downcycling of the recycling process, and sizing application, therefore, the unknown quality of recycled endless carbon fiber sheds risks on pressure vessels producers since the quality of the carbon fiber is the biggest safety concern for pressure vessels (VP1). The pressure vessel producer prefers to purchase virgin endless carbon fiber with a guarantee of the desired quality instead of recycled carbon fiber with unknown quality data and safety risks (VP1).

The challenges of the unclear cost of recycled carbon fiber and underdeveloped carbon recycling technology have roots in the small hydrogen vehicle market and the low volume of the End-of-life CFRP pressure vessels so far. Since hydrogen vehicles have just been introduced into the market and the market share is still small, the volume of CFRP pressure vessels as well as the volume of the End of Life pressure vessels is low, there are only 44 hydrogen vehicles in Sweden so far(European Commission, 2024). Such a low volume of End-of-Life pressure vessels means a very small and unstable supply stream for recyclers, and there is not enough incentive for the recyclers to develop and invest in carbon fiber recycling technology. The low volume of EoL pressure vessels also means that the collecting and sorting of them is not economically feasible. Because only a few recyclers are developing the technology of recycling carbon fiber for the pressure vessel, the cost of recycled carbon fiber is too high.

The small market and low volume of EoL CFRP pressure vessels also cause the problems of a lack of investments in carbon fiber recycling commercialization. The volume of the End-of-Life CFRP has not yet grown to big enough that support capital investment in mass manufacturing facilities (VP3). Even though the recycling technology has already been innovated, because of the low End-of-Life volume, there is still a lack of demonstrated use or empirical business case of the pressure vessels using recycled continuous carbon fiber. Therefore, without a concrete business case, there is not enough supporting investment to scale up the carbon fiber recycling market (VP2). The lack of investment in recycling technology and the low volume of the End-of-Life pressure vessels make the cost of recycling carbon fiber high, which creates a vicious circle. To conclude, the high cost of recycled carbon fiber is mainly due to the low volume of the End-of-Life pressure vessels so far. Because of the low volume, even though the recycling technology is already in place, it's hard to get a business case for continuing investment for scaling up the recycling technology, and the high cost also makes the pressure vessel producers choose not to purchase the recycled carbon fiber, which discourages the development of recycling market.

What makes the situation even worse is that it's very hard to estimate the End-of-Life volume of CFRF pressure vessels and the data about the presence and treatment is rarely found in European countries. This is mainly because the pressure vessels are estimated to have a long lifecycle. Even though the amount of production capacities is known, it's hard to predict the exact time for them to reach the end of life (Colledani & Turri, 2022). VP1 also mentions that since their CFRP pressure vessel is still under development and has not been put into the market, the real utilization data of the pressure vessel is lacking. Therefore, it is hard to tell the lifespan of their products because of the lack of real-life data, which makes the prediction of the End-of-Life pressure vessel volume even harder. Moreover, it's common for vehicles to undergo exportation after the standard lifespan, which makes the prediction of End-of-Life volume from certain regions uncertain, and it makes the supply of the used pressure vessels unclear for recyclers and investors (Colledani & Turri, 2022). To sum up, the low volume, unpredictable, and unstable End-of-Life CFRP pressure vessel supply makes it harder for massive investments in developing a carbon fiber recycling market for pressure vessels.

Apart from the high cost of the recycled carbon fiber, the pressure vessel producers must spend transaction costs on screening the suppliers. Ensuring the Eco-design requires complete screening and traceability of each material and component of the supply chain. The whole supply chain must be aware of and tracing the complex supply chain is costly. Moreover, it also takes a lot of transaction costs to search for suppliers who could provide recyclable and reusable material, this creates an extra financial burden to pressure vessel producers (VP3).

4.4.3 Social and corporative norms

The technology innovation of recycling endless carbon fiber has just been developed and there is an urgent need to scale up and establish the business of recycling endless pressure vessels. However, there is no company eager to take the first step in establishing circularity for its product portfolio and there is no business case to prove the feasibility of recycling the materials (VP3). The pressure vessel producers and recycling technology developer (VP2, RT) agree that there must be a demonstrated use case and business case for recycling and recovering the carbon fiber to attract investment in large-scale endless carbon fiber recycling.

The economic feasibility must be shown to attract recyclers, and they need information about the market size of both the supply and demand. Only when the volume of EoL pressure vessels is high and stable as well as the market demand for recycled endless carbon fiber is growing, there will be a recycling business for pressure vessels. However, the volume of the End of Life pressure vessel production is not clear because of the corporation norms of considering the pressure vessel waste as a problem and concern. Since carbon fiber is very carbon and energy-intensive and is estimated to only have one lifetime without recycling, the carbon footprint of the pressure vessel is considered very negative. Many pressure vessel producers are very secretive about the amount of work they are doing because they see the large volume of pressure vessel waste as a negative profile for the companies (RT). The norms of seeing the pressure vessel as waste and concern make it secretive for pressure vessel producers to disclose the volume of their production. The unclarity or probably underestimated market volume of the pressure vessels makes investors unaware of the potential high EoL pressure vessel volume and makes it harder to attract investors and scale up the carbon fiber recycling market.

4.4.4 Technology

The first technical challenge is the availability of recycled and recyclable materials, especially for endlessly recycled carbon fiber. It's very difficult to recycle the carbon fiber in the pressure vessel and only very few technology innovations are under development. Since the pressure vessels are material composition, the complexity and cross-linked essence of the pressure vessel make recyclability complex (Colledani & Turri, 2022). There is a technical difficulty in separating carbon fiber from other types of fiber and materials such as metal and inorganic powder.

Moreover, the bigger technology challenge is downcycling and it's very hard to regain the endless carbon fiber at the same quality for manufacturing new pressure vessels, downcycling of the carbon fiber is nearly unavoidable for the CFRP pressure vessel. The recycled carbon fiber for pressure vessels must be of the same quality and endless as the virgin carbon fiber, but there are only very limited technology innovation solutions for downcycling so far and there are no recyclers on the market. Currently, the most common recycling technology for carbon fiber is to get short carbon fiber and then use it as filler in plastics, the carbon fiber is cut into pieces while the pressure vessel requires endless carbon fiber.

CFRP is one type of composite that takes about 5% of the total composite market share. Only about 1.5% of all types of composite is recycled and this is mainly because of the wide range of fiber materials, lengths, and processing methods, the diversity of carbon fiber makes it difficult to find a commercial-scale second application for recycling (U.S Commercial Service, 2020). Currently, there are only four companies globally that can provide a continuous supply of recovered carbon fiber, however, the recovered carbon fiber is mainly used for reinforcement, anti-static properties, and improving war resistance, which is not applicable for pressure vessels (J. Zhang et al., 2023). The current recycling technology for carbon fiber is to cut them into pieces and use them as fillers. This kind of recycled carbon fibre can't be used in the conventional composite manufacturing process because they are loose and non-continuous. However, the existing carbon fiber recycling method cannot fulfill the quality requirement of the pressure vessel, which has the highest quality requirement for carbon fiber. Even though innovations and projects are going on to provide the solutions, only a few succeed (VP1).

The usage of recycled carbon fiber will also shed extra risks on pressure vessel production. The complexity of the pressure vessel leads to sluggish and vulnerable processes and there is a technology risk by switching into new recycled material. Especially if the value chain and design have already been established in production, the replacement of recycled materials may also corrupt the production due to its complexity, which will expose more risks to the pressure vessel producers (VP3).

To sum up, the biggest difficulty of carbon fiber recycling technology is downcycling, which makes the quality of the recycled carbon fiber could not fulfill the high requirements of pressure vessels. Even though a few technological innovations have already been developed to solve the downcycling problems, it has not been scaled up and commercialized. Another technological concern is about the quality risks due to the uncertainty of the quality of the recycled carbon fiber as well as the integration of recycled materials into the existing design and production. Figure 4-5 summarises the challenge of recycling the Type IV CFRP pressure vessels.

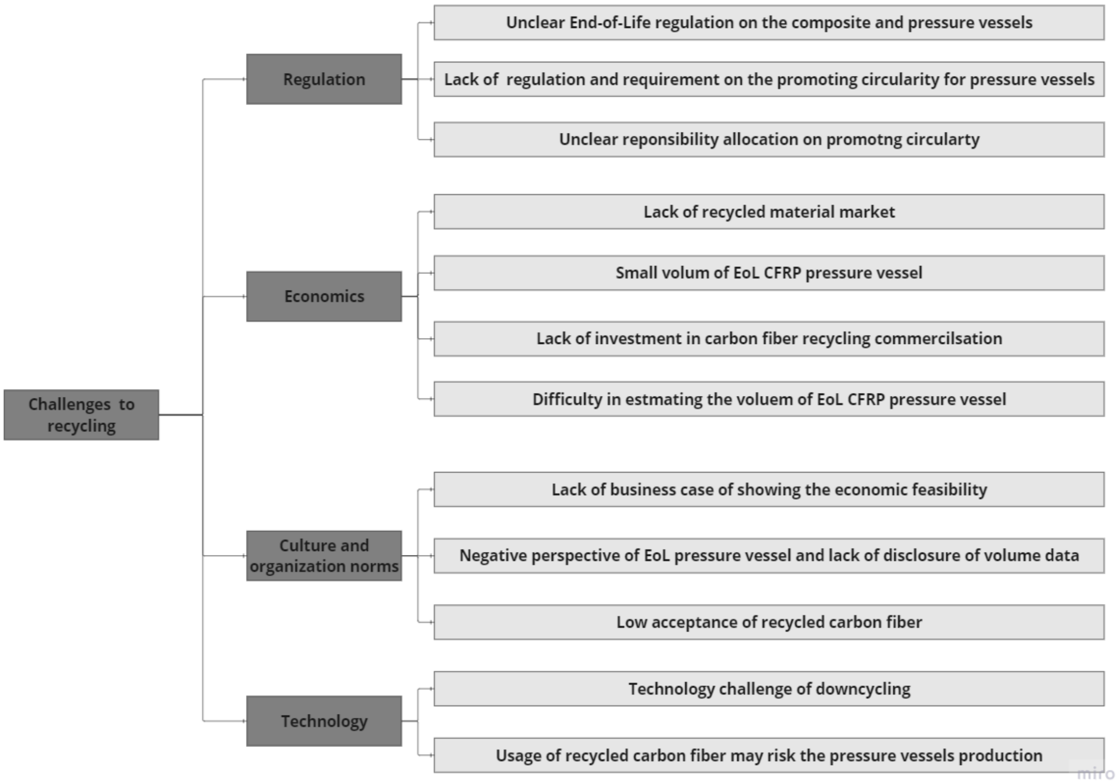

Figure 4-5 'PEST analysis of the challenges of recycling the Type IV CFRP pressure vessels'

4.5 The Opportunities of the Circular Economy Strategies

While some external challenges are discovered in developing the eco-design and recycling the carbon fiber to manufacture new pressure vessels, there are also positive opportunities from regulation, economics, social and corotational norms as well as technology. The following section will use the PEST framework to analyze the external factors that bring opportunities to promote recycling actions for Type IV CFRP pressure vessels.

4.5.1 Regulation

One of the biggest regulation opportunities is the upcoming renewed version of the End-of-Life Vehicle Directive (ELV) (2023/0284 (COD), 2023), which promotes circularity by banning landfills, requiring a minimum level of recyclable and recycled materials, covering more vehicles, and applying the Extended Producer Responsibility (EPR). Table 4-3 summarizes the main requirement pillars of ELV.

The first requirement pillar of ELV is waste management. With increasingly stringent regulations and costs on the landfill, the waste treatment of the EoL pressure vessels has become an issue for the pressure vessel producer, dismantlers, and recyclers to consider (RT). The upcoming renewed version of ELV proposed a landfill ban for automotive shredder residue fraction and set ambitions on improving the recovery of key components of End-of-Life vehicles (Article 35).

The second requirement pillar of ELV is the requirement for the recyclability of vehicle components. The upcoming renewed version of ELV proposes a medium ambition level with plastics recycled content targets of 25% for vehicles by 2030 (Article 6). The ELV also regulates that the content of reusable or recyclable material in a vehicle is a minimum of 85 % by mass or that the content of reusable or recoverable material to a minimum of 95 % by mass (Article 4). Considering that pressure vessels are one of the crucial components of gas vehicles by mass, pressure vessels which are designed reusable, recyclable, or recoverable are likely to be favored by the vehicle manufacturers to fulfill the requirements. Moreover, the pressure vessels are Carbon Fiber Reinforced Plastics, which means that the pressure vessels with recycled materials will help vehicle producers achieve the 25% recycled plastic target. Considering that the CFRP pressure vessels can hardly be recycled and recovered currently, vehicle manufacturers will reconsider their materials choice of pressure vessels and put more pressure on CFRP pressure vessel producers to design pressure vessels more recyclable and prefer pressure vessels with recycled materials.

Sweden has already implemented Extended Producer Responsibility for passenger cars, buses, and lorries with a total weight that does not exceed 3,500 kg from May 2023, the vehicle producers are responsible for covering the financial and/ or physical responsibility in collecting and disposing of the EoL vehicles (The Swedish Environmental Protection Agency, 2023). The EPR also regulates that vehicle manufacturers need to exchange information with their downstream actors, which could facilitate more circular economy actions. Table 4-2 summarizes the information that is required to be provided by vehicle producers to the potential car buyers in EPR (Sweriges Riksdag, 2023) All the required information is identified as helpful and needed for promoting circularity in the study.

Table 4-2 'Information required to be provided by vehicle producers by EPR'

Type of information	Description of information
Technical information	The construction of the cars and components about possibilities for material recycling and other recycling
Technical information	How the cars are intended to be taken care of when they are used up so that they are disassembled, drained of fluids, and otherwise handled in an environmentally acceptable manner
Technical information	What is being done in terms of developing the best possible methods for reuse, recycling, and other recycling of end-of-life cars and their components
Technical information	What progress has been made to reduce the need to dispose of waste arising from end-of-life cars and their components in favor of increased material recycling and other recycling
Technical information	Information about materials, components, and hazardous substances in the cars that are needed to facilitate reuse and recycling
Market information	End-of-life cars and car parts can be left free of charge at a reception system
Market information	Where end-of-life cars and car parts can be left
Sustainability campaign	The importance of an end-of-life car or car part is disposed of in an environmentally acceptable way, considering the presence of hazardous substances
Technical information	The recycling and reuse result that the return contributes to, and the importance of reducing litter

Source: Adopted from '(Sweriges Riksdag, 2023)'

The EPR also requires that the information must be shared and provided to the potential car buyers in the form of brochures, information sheets, or websites. They also must ensure that the car scrappers and equivalent actors in the Member States of the European Union have access to the disassembly instructions. The coding standard is required to be used for the components to facilitate identification.(Sweriges Riksdag, 2023)

Table 4-3 "End-of-Life Vehicle Directive and its impact on the pressure vessel industry

The regulatory principle	Detailed requirements	The direct effect on pressure vessels
Design Circular	Better vehicle design in promoting recyclability, reusability, and recoverability. reusable or recyclable to a minimum of 85 % by mass; reusable or recoverable to a minimum of 95 % by mass. Better compliance verification exchange information with the dismantling sector	Vehicle manufacturers need to purchase recyclable and recoverable pressure vessels Vehicle manufacturers provide detailed and user-friendly dismantling and recycling information, including the use and location of critical raw materials in vehicles
Use recycled content	Set mandatory recycled target for plastics in newly type-approved vehicles that 25% of plastic is recycled from post-consumer plastic waste, and that 25% of such material should come from recycled end-of-life vehicles	Vehicle manufacturers purchase pressure vessels with recycled materials
Treat better	a ban on landfills for automotive shredder residue fractions Mandatory removal of certain parts/components before shredding to encourage their recycling or reuse	Vehicle manufacturers purchase pressure vessels that should not be landfilled. Dismantlers remove the pressure vessels and avoid shredding
Collect more	Better tracking of ELVs through digitalization and exchange of information on national vehicle registers.	The volume and location of EoL vehicle will be clearer
Incentives to increase collection of ElVs and improve waste treatment	Establishment of an Extended Producer Responsibility scheme (EPR) for vehicles, the vehicle manufacturer covers the costs including, the collection of end-of-life vehicles, the costs of conducting awareness-raising campaigns; establishing a notification system, data gathering and reporting	Vehicle manufacturers cover costs linked to the collection and high-quality treatment of ELVs
Cover more vehicles	Extension of the scope of EPR to L-category vehicles, lorries, buses, and trailers	More vehicle manufacturers are included in the EPR

Source: Adopted from '(2023/0284 (COD), 2023)'

Other than the EVL and EPR, the hydrogen economy is encouraged by public authorities to combat climate change. EU's "A hydrogen strategy for a climate-neutral Europe" (COM(2020) 301 final, 2020) encourages the wide adaptation of the hydrogen economy, which means that the hydrogen ecosystem will bloom and scale up rapidly in the next decades. It's not far from the pressure vessel hitting the large production levels (RT). The expected increasing volume makes the End-of-Life treatment of the pressure vessel a concern as well as increasing the demand for carbon fiber. While there is a demand-supply gap for virgin carbon fiber for pressure vessels, the opportunity to use recycled carbon fiber is more desirable for pressure vessel producers.

4.5.2 Economics

The first economic opportunity comes from the growing market of hydrogen vehicles and pressure vessels. As hydrogen is considered the alternative to fossil fuel in mobility, EU is aiming to achieve wide adoption of hydrogen by 2050 by encouraging the adoption of hydrogen in heavy-duty road transport, rail, waterborne, and aviation (COM(2020) 301 final, 2020). It's estimated that 2 million vehicles in Europe will be hydrogen vehicles equipped with pressure vessels by 2030, and the amount of pressure vessels is expected to be 4 million (U.S Commercial Service, 2022). Since the CFRP pressure vessel is the most used pressure vessel for hydrogen vehicles, with the expected growing hydrogen application in the mobility sector, the demand for CFRP vessels is also expected to expand. According to (J. Zhang et al., 2023), the global market size for CFRP pressure vessels is projected to reach 1.96 billion USD by 2026, at an annual growth rate of 5.2% (from 2022 to 2026) from 1.45 billion USD in 2020. The carbon fiber used in the pressure vessel is expected to double in 2024 compared to the level of 2021 because of the hydrogen storage demand in the mobility industry. The increasing volume of CFRP pressure vessels will facilitate the development of the carbon fiber recycling market because of the large volume of EoL pressure vessels (VP1). Figure 4-6 shows the carbon fiber demand in the pressure vessels from 2004 to 2026.

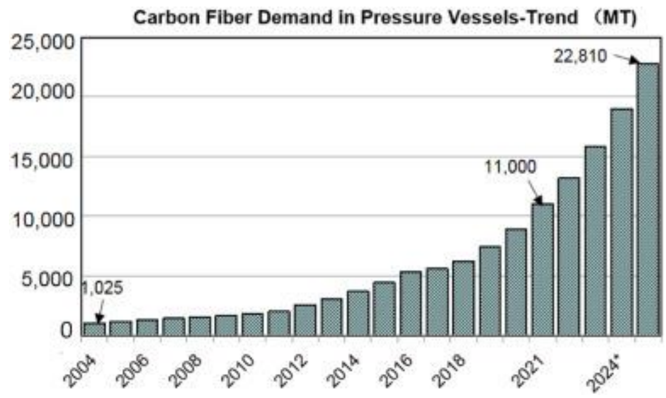

Figure 4-6 'Global carbon fibre demand from pressure vessels from 2004 to 2025'

Source: 'Copyright 2022, ATA Carbon Fiber Tech Guangzhou, (J. Zhang et al., 2023)'

The growing demand for CFRP and carbon fiber will enlarge the supply-demand gap of carbon fiber, which creates opportunities for recycling carbon fiber. The figure 4-7 shows that the pressure vessel application consumed about 9.3% of the CFRP in the whole CFRP market in 2021 with a rapidly increasing demand trend foreseen. (National Composite Center, 2024) of UK predicted that the demand for carbon fiber is expected to grow 5-fold between 2025 and 2030, which will exceed the production capacity. (J. Zhang et al., 2023) predicts that the volume of hydrogen fuel cell automotive vehicles is expected to reach 3 to 4 million globally in 2030, and the corresponding carbon fiber demand in pressure vessels will also reach 180kt by that time. However, there is a supply-demand gap in the carbon fiber industry, a report in 2019 estimated that the carbon fiber annual demand will exceed the supply capacity by 24,000 metric tons in 2022 (Composites World, 2019). Considering carbon fiber is the most crucial material for CFRP pressure vessels, the supply-demand gap of virgin carbon fiber is predicted that the rapidly growing demand will make pressure vessel producers consider utilizing recycled carbon fiber, which creates a huge market for recycled carbon fiber(U.S Commercial Service, 2022). Additionally, the carbon fiber supply-demand gap is more severe for pressure vessels because of the high-quality demand for carbon fiber. Toray's T700S is the standardized type of carbon fiber that pressure vessel producers utilize (Sloan, 2023), however, meeting the carbon fiber demand for the pressure vessel is considered a challenge. Some estimations point out that the total market demand for hydrogen pressure vessels is about half a million by 2025, which makes the supply of virgin carbon fiber is huge challenge (Sloan, 2023). With the growing demand for carbon fiber for pressure vessels, the price of virgin materials will increase, and recycled carbon fiber will be a preferred option for pressure vessel producers (RT).

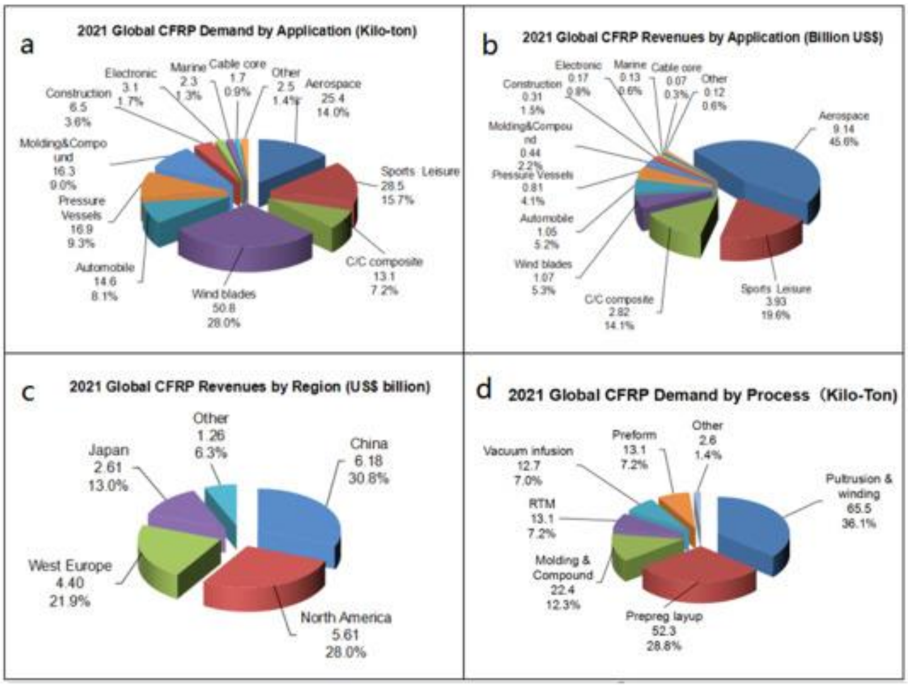

Figure 4-7 ' Global demand for CFRP composites in Year 2021 by (a) application and (d) process; Global CFRP composites revenues in Year 2021 by (b) application and (c) region'

Source: 'Copyright 2022, ATA Carbon Fiber Tech Guangzhou (J. Zhang et al., 2023)'

Another economic opportunity comes from the high value and price of virgin carbon fiber. The cost of virgin carbon fiber is 4 to 40 times higher than the price of glass fibers depending on the specific application (Colledani & Turri, 2022). Virgin carbon fiber can cost 20 to 40 £/kg in the UK (Li et al., 2016) and 5-20 USD per square meter in the US in 2020 (Borjan et al., 2021), which is the main raw material cost for the CFRP pressure vessel producers (VP1). The price of recycled carbon fiber is around 40% lower than virgin carbon fiber (Composites World, 2019). The recycling technology provider of the pressure vessels estimates that the cost of recycled carbon fiber will be lower than virgin carbon fiber and the cost will decrease with a bigger volume of End-of-Life pressure vessels and more mature technology development (RT). Additionally, the high residual value of the carbon fiber in the EoL pressure vessels will create huge incentives for recycling and reusing the carbon fiber, especially with the increasing demand for carbon fiber in pressure vessels.

4.5.3 Social and corporative norms

The high energy intensity in virgin carbon fiber production has a huge environmental impact and a negative image on pressure vessel producers. With the growing social and regulatory concern of sustainability, using recycled carbon fiber will help pressure vessel producers to reduce their carbon footprint as well as improve their corporate image. The production of virgin carbon fiber is around 25kg Co2 eq per kg, which is 10 times more carbon emission intense than the production of steel (Kawajiri & Sakamoto, 2022). Another study estimated that the GHG emission is 29.45 metric tons of Co2 eq per ton of virgin carbon fiber compared to 4.65 metric tons of GHG emission from recycled carbon fiber (Composites World, 2019). The huge negative environmental impact of using virgin carbon fiber is one of the main drivers for pressure vessel producers to replace virgin carbon fiber with recycled carbon fiber (Li et al., 2016). The social preferences for recycled materials will also encourage pressure vessel producers to integrate recycled carbon fiber.

Another social pressure comes from the sustainable narratives of the hydrogen economy. As hydrogen is considered one of the biggest alternative clean energies for industry and mobility sectors, sustainability and circularity are the major topics and narratives for the whole value chain. Pressure vessels as part of the hydrogen ecosystem must respond and align themselves to the sustainable narratives of the whole hydrogen economy, where the social norms and pressure are pushing the pressure vessel industry for circular transition (VP3).

4.5.4 Technology

The biggest technology challenge of recycling carbon fiber from pressure vessels is downcycling, however, with more attention from both governments and corporations, several technology innovation projects have been carried out and some of them have successfully solved the downcycling challenges. A recycling technology innovation could reclaim the carbon fiber from the resin matrix without chopping and weakening, which could be used to reclaim the carbon fiber from the used CFRP pressure vessels (National Composite Center, 2024). The technology innovation has shown that the continuous carbon fiber from a used pressure vessel has been successfully reclaimed and reused in manufacturing a new pressure vessel in 2022. Technological innovation has solved the down-cycling problem and allows any length of carbon fiber to be retained. The research and development phase has almost been done by the recycling innovation company and waiting to be scaled up and commercialized (RT).

To sum up the opportunities regarding promoting the recycling CE action of Type IV CFRP pressure vessels. In terms of regulation opportunities, the upcoming End-of-Life Vehicle Directive and EPR on vehicles require the vehicle producer to design more circularly, use more recycled materials, and invest in end-of-life management, which will provide market opportunities for pressure vessels that contain recycled materials and are designed for circularity. Moreover, the hydrogen economy is encouraged by the EU to combat climate change and the market and volume of EoL pressure vessels are expected to grow. In terms of economic factors, the growing volume of EoL pressure vessels will facilitate the technology innovation and recycling market, the growing supply-demand gap of virgin carbon fiber will encourage the use the recycled carbon fiber, and the high residual value of the EoL pressure vessel creates incentives for recycling market. In terms of the culture and organization norms, with growing concern and public preference for sustainability, the usage of recycled carbon fiber will hugely reduce the carbon footprint of pressure vessels and create a positive corporate image. The sustainable narrative of the hydrogen economy also put circularity requirements and expectations on the pressure vessels. Regarding the technology side, there are several recycling technological innovations in solving the downcycling challenge and some have succeeded. Figure 4-8 summarizes the opportunities for recycling the Type IV CFRP pressure vessels.

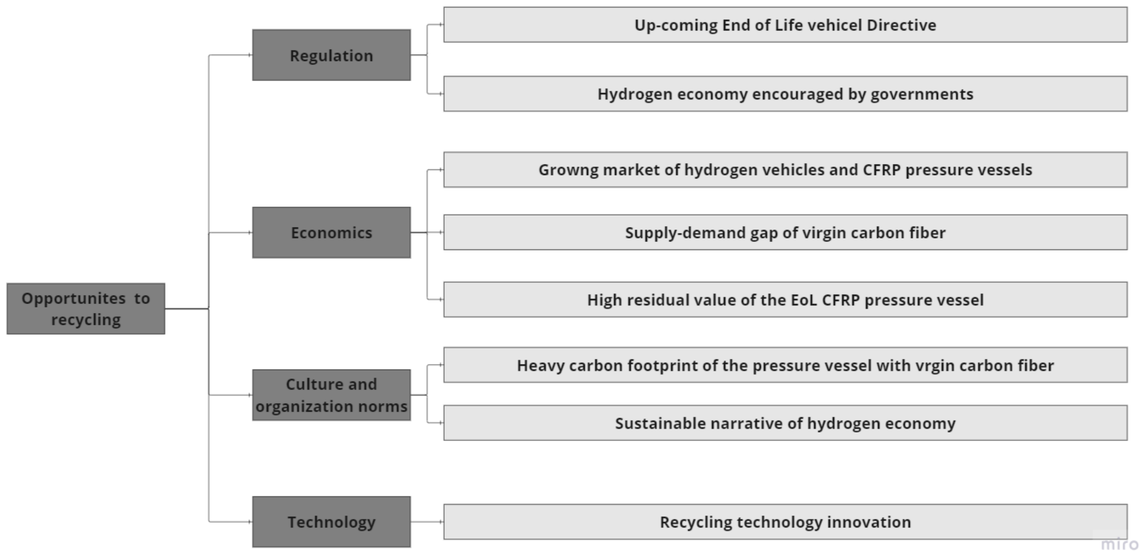

Figure 4-8 'PEST analysis of the opportunities in the recycling action of Type IV CFRP pressure vessels'

5 Discussion

5.1 Why certain CE strategies are more common?

5.1.1 Why is recycling more common than reusing Type I pressure vessels?

Regarding the Type I pressure vessels, the most common CE strategy is recycling while reusing is very limited. According to the waste hierarchy, the reuse actions are superior to the recycling actions in terms of circularity and sustainability performance. In this section, the reasons why there are limited reusing action is discussed from both the supply end and the demand end. From the supply end, there is only a small volume of the reusable used pressure vessels provided by the dismantlers; on the demand side, the demand for the used pressure vessels is also low.

From the supply side of the used pressure vessel. The volume of the End-of-Life gas vehicle is very small, which means the volume of reusable pressure vessels is also limited. As shown in figure 4-1, 2784 gas vehicles were deregistered from Sweden in 2023, however, 1960 of them, which is about 70% of the gas vehicles were exported to other countries. This status shows that only around 800 gas vehicles were dismantled domestically in Swedish. It means that every dismantler only receives one or two gas vehicles every year (VD1, VD2, VD3). Such a small volume makes recycling the easiest and most convenient CE strategy the dismantlers decide to use. Moreover, since the gas vehicle market is decreasing, many dismantlers do not foresee the potential market for the used pressure vessel, therefore, they choose to sell them as scrap fractions instead of spare parts.

Another reason is because of the strict inspection requirement on pressure vessels limits the volume of reusable pressure vessels. Due to safety concerns, the pressure vessel must fulfill the inspection requirements for continuing use. The dismantlers use the inspection requirements made by the Swedish government to decide the reusability of the pressure vessels. However, only around 20% of the used pressure vessels can fulfill the strict inspection requirement and are applicable to be sold. The most common reason for failing the inspection is because the bad quality painting of the pressure vessel makes them easily get rusted, which is considered a safety concern. Therefore, 80% of the used pressure vessels are not reusable (VD4). Considering most dismantlers sell all the pressure vessels as scrap no matter their reusability, the actual volume of reusable pressure vessels is lower than the theoretical estimation and is very limited. Such a low volume of reusable pressure vessels makes it even more difficult to match the specific demand of the potential buyers, which means very few reusable pressure vessels could eventually be reused.

From the demand side, the reasons include the decreasing market demand as well as the social preference of the new pressure vessels. The volume of gas vehicles has been decreasing since 2017 in Sweden, which means the overall demand for the used pressure vessel is decreasing. The decreasing gas vehicle market is also one of the main reasons the dismantlers choose not to resell the pressure vessel because they estimate the demand for used pressure vessels is very small. Another reason is the social preference for buying new pressure vessels instead of used ones due to safety concerns. The demand for purchasing pressure vessels is because the gas vehicle failed the annual inspection and had to be replaced to fulfill the inspection requirements. In this sense, purchasing the used pressure vessel may risk the gas vehicle failing the inspection again. Moreover, due to the potential safety concern of the used pressure vessel, gas vehicle owners tend to choose a new pressure vessel instead of the used one (WS2), the workshop is also concerned about the brand reputation from buying the used pressure vessels (ME). In terms of economic feasibility, purchasing the used pressure vessels means extra work, costs, and higher transaction costs. Considering the cost of purchasing new pressure vessels is not so high because of the low price of the raw material metal, the used pressure vessels do not have many cost advantages (WS2).

5.1.2 Why eco-design is the most common CE strategy for Type IV CFRP pressure vessels?

The most common circular action regarding the Type IV CFRP pressure vessels is eco-design including reducing the complexity of materials and purchasing recycler and recyclable materials while material recycling is still in the stage of market development. The biggest reason is the low volume of EoL pressure vessels on the market currently. Even though the volume of hydrogen vehicles is expected to grow in the following years, the current volume of hydrogen vehicles is still very low. The statistics from (European Commission, 2024) show that by the end of 2023, there were 44 hydrogen fuel cell electric passenger vehicles and 2 buses registered in Sweden and there are no fuel cell electric light commercial vehicles or trucks. Considering the lifespan of the hydrogen vehicle could be more than 10 years, the existing volume of EoL pressure vessels is very limited. Moreover, because of the negative narrative of the pressure vessel waste, it's very hard to predict the current volume of the EoL pressure vessels. Therefore, the low volume of EoL CFRP pressure vessels currently makes the circular actions from downstream such as recycling very limited, and more efforts are from upstream design instead.

5.2 The critical information for the CE strategies of Type I pressure vessels

5.2.1 What is the critical information

Among all the key actors in the recycling and reusing actions for the Type I pressure vessels, the dismantlers are the most crucial decision makers since they are the first and most direct owners of the used pressure vessels. Their decision of whether to sell the used pressure vessels as scrap fractions or as a reusable spare part hugely decides whether the used pressure vessel gets recycled or reused. Additionally, their decision is hugely influenced by the information they receive. In this section, the comparison of the decision and the information behind recycling and reuse is shown.

The first type of crucial information is market information, which includes the market information about the material inflow as well as the potential downstream buyers. In the recycling process, the vehicle users, workshops, and dealers need the market information of local dismantlers, the vehicle dismantlers need the market information of EoL vehicle sellers, and the recyclers need the supply information from dismantlers. In the reuse actions, vehicle users, workshops, and dealers need the market information of local dismantlers, and dismantlers need the market information about the supply as well as the potential reusers, and the reusers need the supply information from dismantlers.

The different market information and predictions about the potential buyers for the used pressure vessels hugely influence the circular actions regarding the pressure vessels. Even if the market demand exists, the information about the demand is the biggest difference between the dismantlers who sell pressure vessels as spare parts and the dismantlers who sell them as scrap. The prerequisite for the dismantlers to sell the pressure vessel as spare parts is because they identify that there is a market and potential buyers for the used pressure vessel. Only after they recognized the potential demand for reused pressure vessels, did they decide to make the inspection and then sell them to make a business. If the dismantlers do not foresee the potential buyers as well as have negative predictions on the decreasing gas vehicle market, they will choose to sell used pressure vessels as scrap. Only after dismantlers notice the potential market for the used pressure vessel as well as have a positive prediction on the growing market for the gas vehicle market, they will sell the pressure vessel as spare parts.

The second type of critical information is regulation. For dismantlers, the regulation regulates the dismantling process of the dismantlers. Additionally, the requirement that the manufacturing date of the pressure vessels must be disclosed helps dismantlers get the lifespan information. The inspection requirements provide an inspection protocol for dismantlers to identify the reusability of the used pressure vessels more efficiently. The end user in the reusing action also needs the inspection regulation as a guideline for checking the quality of the used pressure vessels in trading with dismantlers.

The third type of critical information is technology information, which is especially important for vehicle dismantlers. The technology information includes the dismantling manuals and lifespan information of the pressure vessels, which will help dismantlers take out the pressure vessels more efficiently and decide the reusability more quickly. For the end users in the reusing process, the technology information includes the identification information, the quality of the pressure vessels as well as the installation manuals. Figure 5-1 shows the key action points and information needed for dismantlers to conduct recycling and reuse actions.

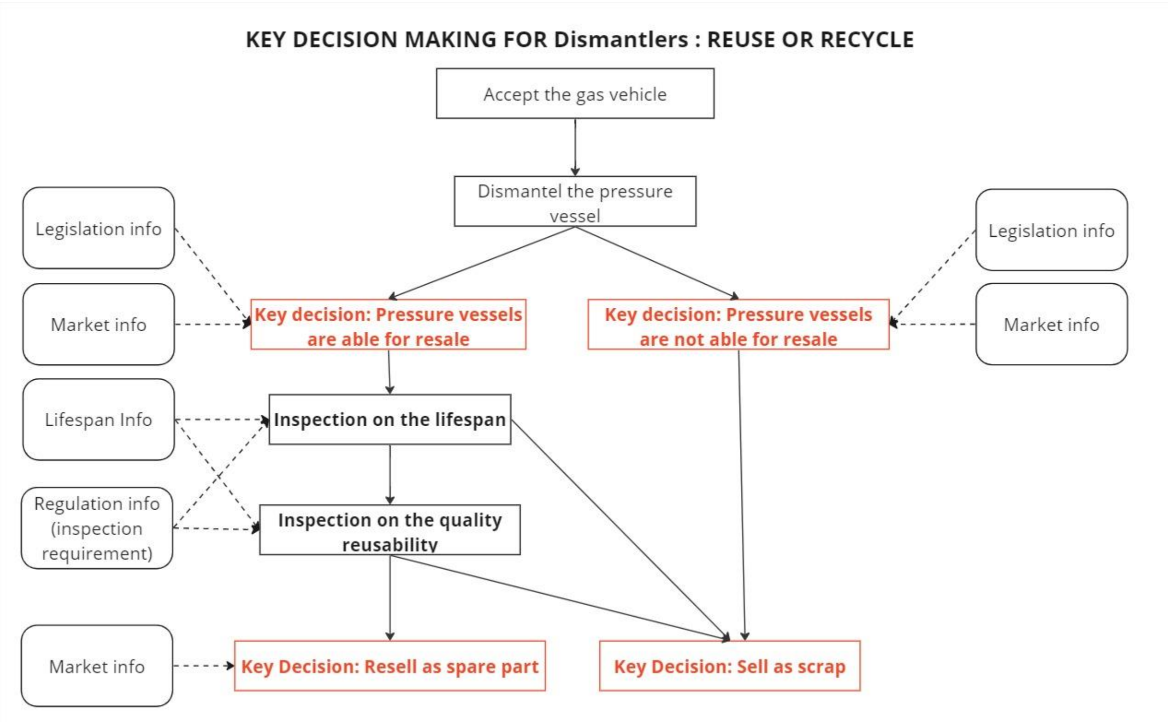

Figure 5-1 'Critical information for dismantlers in deciding the recycling and reusing CE strategy'

To sum up, regarding the Type I metal pressure vessels, recycling actions are most applied while few of them are undergoing reuse actions. The most important information deciding the circular actions is the market information about the potential reusers. Recognition of the potential buyers of the used pressure vessels decides the dismantlers' action on selling the pressure vessels as scrap for recycling or spare parts for reuse. The regulation and technology information are also critical in deciding the reusability of the pressure vessels.

5.2.2 How has the critical information been shared and the challenges?

As mentioned above, the market information of the potential buyers of the used pressure vessels is the prerequisite for the dismantler to sell the used pressure vessels as spare parts. To promote more reuse actions, the market information about the potential spare part buyers must be informed to dismantlers. The market information could come from dismantlers' knowledge once they realize that market need comes from the strict third-party inspection and lifespan limitation of pressure vessels. Apart from the internal knowledge, the demand for market information could also come from the dealers' network (VD5). The brand-owned dismantlers, dealers, and workshops have daily communication and data exchange platforms for commuting demand and supply. The brand-owned dismantlers receive requests from the workshops, and they recognize the market demand for the pressure vessels as spare parts (VD5). The brand's internal network between dealers, dismantlers, and workshops not only works as an information-sharing platform but also reduces transaction costs. To promote more reuse actions, the dismantlers must be informed of the demand of the market and the value of the pressure vessels.

After dismantlers recognize the market demand, they need to find potential buyers for the used pressure vessels, the dealers' networks and the internal information-sharing platform are the main tools for exchanging the supply and demand information between brand-owned dismantlers and workshops. For dismantlers who are not owned by vehicle manufacturers, the independent used-part trading website is commonly used as a marketplace and service provider for trading spare parts of vehicles. The trading market is a communication and information exchange platform for individual vehicle owners, workshops, and dismantlers. To make a purchase decision, the dismantlers need to provide technical information about the products such as usage period, current condition, price, and so on. To make the trading more efficient, the most important step is to identify whether the used part fits the buyers' vehicles (TP). To make the identification process easier, the used-part trading website provides guidelines for the dismantlers to state specific kinds of information to make it easier for the buyers to determine whether the used part is suitable for their vehicle. According to the trading website, the article number is the most important for identification (TP). Although there is no tool currently to precisely identify whether the used part is exactly suitable for the buyers' vehicle, the information plays a crucial role in the trading. The more data the dismantlers provide, the greater the chances the used car parts could match the buyers' demand and reduce the transition cost for both the buyers and sellers.

The regulation information about the dismantling and inspection requirements is publicly accessible for all the key actors, therefore, the information sharing channels are through the public authorities' webpages.

The technical information is important for the dismantlers, the information could help to dismantle the vehicles more safely and efficiently as well as help dismantlers identify the reusability of the pressure vessels. The regulation plays a huge role in facilitating information sharing, the rule that pressure vessel producers must disclose the manufacturing date of the pressure vessels makes the lifespan of the pressure vessels communicated to the dismantlers, which helps them identify the lifespan more efficiently.

To conclude, to promote more reuse actions, the market demands information about the potential spare part buyers must be shared with dismantlers. The brands' internal network among dealers, workshops and brand-own dismantlers helps provide the market demand for dismantlers. For the market information between vehicle dismantlers and end users in the reuse process, the brand-owned internal communication platform and the third-party spare part trading platform are the main information-sharing channels. For the technology information sharing flow, except the lifespan information is shared between pressure vessel producers and dismantlers, which is regulated by law, there is rarely communication between vehicle producers and vehicle dismantlers.

5.3 Suggested information model for the recycling Type IV CFRP pressure vessels

Considering the volume of the EoL CFRP pressure vessels is very limited currently, the main circular initiative is Eco-design, including reducing the complexity of the pressure vessels and using recyclable materials. With the expected growing volume of the EoL CFRP pressure vessels in the future as well as the development of recycling technology of carbon fiber, the CE actions of recycling the carbon fiber from used pressure vessels and then reusing them into manufacturing new pressure vessels is a potential CE action for CFRP pressure vessels. Since there is no empirical business case and example of such recycling cases, based on the findings of the Type I pressure vessels' circular initiatives and interviews with key stakeholders, the key action points and information needs are identified. To recycle CFRP pressure vessels, the key actors are pressure vessel producers, dismantlers and pressure vessel recyclers. Here are the assumed key action points of each of the actors and the information needs.

The first actor is the pressure vessel producer, and their role is both the pressure vessel material suppliers and the end users of the recycled material from used pressure vessels. As pressure vessel producers and material providers, their action is to design the product in a recycle-friendly way such as reducing the complexity of the materials and designing the pressure vessel in a more recycle-friendly way. For the role of the end user, their action is purchasing and using the recycled carbon fiber from EoL pressure vessels. To achieve these actions, they need market information about the providers of recycled carbon fiber, and they also need to ensure the quality of the carbon fiber can fulfil the high-quality demand, the cost is also a concern when they choose to purchase recycled material or not. All the information should be provided by the pressure vessel specialist recyclers who will sell their recycled carbon fiber to the pressure vessel producers. The most critical information for pressure vessel producers is the quality of the recycled carbon fiber. The quality of the recycled fiber depends on many factors including the quality of the virgin fiber, downcycling of the recycling process, sizing application and so on. However, carbon fiber is the critical material to ensure the quality and safety of pressure vessels, and the uncertainty of recycled carbon fibre's quality is one of the biggest barriers for pressure vessel producers to use recycled materials (VP1). Therefore, the negative corporative perception and safety concern of recycled material should be minimized by adequate communication between pressure vessel carbon fiber recycling specialists and pressure vessel producers.

The second actor is the dismantlers, they are the material supplier who provides and sells the used pressure vessels for the recyclers. The first key action is to receive the gas vehicle, where the market information of the material inflow and the location of the used hydrogen gas vehicle is needed. This information is provided by the vehicle users, workshops and dealers who will sell the End-of-Life hydrogen vehicle to the dismantlers. The second key action is to dismantle the gas vehicle and take out the pressure vessel in a safe way, which needs the dismantling manuals provided by the vehicle producers as well as the regulation from the public authority. The third action is to sell the pressure vessels to the pressure vessel specialist recyclers. The information needed is the values of the pressure vessels and the market of the recyclers. The information about the residual value of the used pressure vessels is the prerequisite, only when the dismantlers identify the huge residual value of the pressure vessel as well as recognize the market of pressure vessel specialist recycler, they will decide to sell the pressure vessel to the specialist pressure vessel recyclers instead of a general recycler for car scrappers. The value and market information should be provided by the pressure vessel recyclers since they rely on the dismantlers for supplying the used pressure vessels. The final action of the dismantler is to sell the pressure vessel to the pressure vessel specialist recyclers. Another information needed is the market of the recyclers, who are dismantlers downstream buyers, which is provided by the pressure vessel recyclers.

The final key decision maker is the pressure vessel specialist recyclers, their role is the technology providers for recycling the pressure vessel and then selling the recycled carbon fiber to the pressure vessel producers. Their first action is to receive the used pressure vessel from the dismantlers, where information about material inflow and dismantlers is required. The volume of the End-of-Life pressure vessel will also help recyclers to estimate the material inflow. This kind of information should be provided by the dismantlers as well as the pressure vessel producers. The second action point is to recycle the pressure vessels. In this process, the design information of the pressure vessel will help the recyclers do the work more efficiently, especially knowing the winding patterns will help the recyclers unwind the tow and recycle the carbon fiber much more efficiently (RT). The final action point is to sell the recycled materials to the pressure vessel producers. The information needed is the market information of the pressure vessel producers who will potentially purchase recycled carbon fiber. Figure 5-2 below shows the key actors, actions, information needs and sources in the recycling action of Type IV CFRP pressure vessels. A detailed table can be found in the appendix.

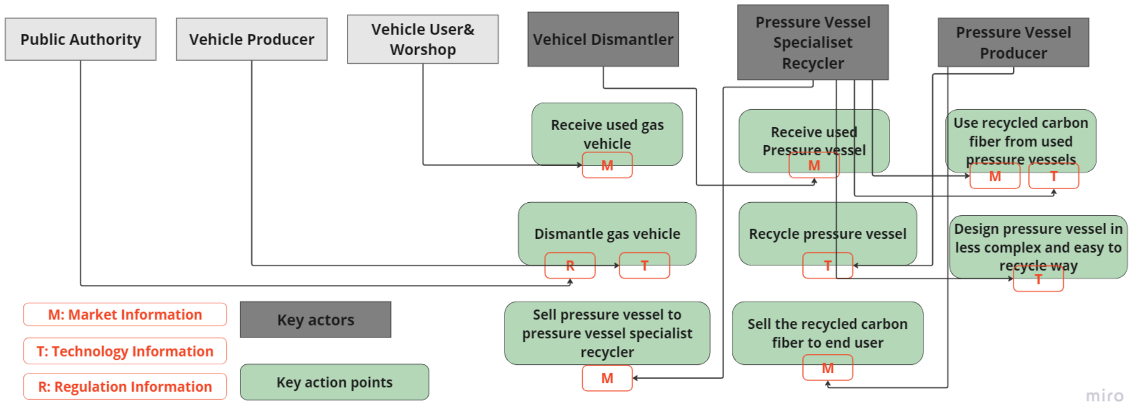

Figure 5-2 'Key actors, actions, information need and sources in recycling action of Type IV CFRP pressure vessel'

5.4 Compared to previous studies about critical information need

Information works as a catalyst for promoting the circular economy has been proved and agreed upon by previous studies as well as this research, however, different scholars have different opinions on what kind of information is critically needed for the stakeholders. Previous studies have identified the key information needs in industries such as agriculture, construction and the electronic industry. This study identified the critical type of information in the reuse and recycling actions of pressure vessels in mobility applications. In this section, a comparison is made between the findings of this study and previous research in terms of what is the critical information needed and the reasons why is discussed. Table 5-1 below summarizes the comparison.

Table 5-1 'Comparison to previous studies in the critical information need'

The CE strategy	The critical information	Reference	Applicable in this study or not
Reuse	History of product	(Jäger-Roschko & Petersen, 2022; Luoma et al., 2021)	No
Reuse	Customer behaviour & utilization	(Jäger-Roschko & Petersen, 2022; Luoma et al., 2021)	No
Reuse	Market and material flow	(Luoma et al., 2021)	Yes
Recycling	Material composition	(Jäger-Roschko & Petersen, 2022)	No
Recycling	Location	(Ferguson & Browne, 2001)	No
Recycling	Utilization	(Ferguson & Browne, 2001)	No
Recycling	Market and material flow	(Luoma et al., 2021)	Yes
Recycling	Regulations	(Jensen et al., 2023)	Yes

For reuse actions, the critical information identified by previous scholars includes the customer behavior and utilization information, the history of the products such as use, status and conditions (Jäger-Roschko & Petersen, 2022; Luoma et al., 2021) and the customers are the main source of the information. This kind of information helps identify the reusability of the products, which reduces the necessity of manual inspections. However, they are not critical information for reusing the pressure vessels in mobility applications. The reason is that safety is the biggest concern for pressure vessels, no matter whether the current condition or product history information is gained, the inspection of the used pressure vessels is unavoidable due to safety concerns. The inspection is the unavoidable prerequisite to deciding the reusability of the used pressure vessels, and the inspection guidelines provided by public authority are the most critical tool and the only information needed for dismantlers to decide the reusability.

The customer behavior and utilization information are also not crucial in the reusing of pressure vessels in mobility applications. Unlike items such as textiles, furniture or electronics which are directly consumed by consumers and the condition changes with utilization behaviors, vehicle users do not directly utilize the pressure vessels, and the reusability and quality of the pressure vessels are not hugely influenced or changed by the customer's behavior. That's the main reason why the customer behavior information is not critically helpful for pressure vessel reusing. Unlike components such as vehicle batteries where temperature, driving distance, and driving habits hugely influence their reusability, pressure vessels require minimum repairing and the quality of it does not change with utilization conditions. Therefore, the product, utilization data and condition do not influence the reusability of pressure vessels, and the customers are not crucial information providers either.

On the other hand, agreed with the previous research, the market and material flow information are extremely important for reusing pressure vessels. One of the main reasons that there is limited reusing action is due to the small volume of EoL gas vehicles and the unawareness of the potential buyers, and reusing is not widely aware of as an option. The dismantlers need to be aware of the market demand of used pressure vessels while the workshops and individual vehicle owners need to be aware of the supply of used pressure vessels as well.

For recycling actions, previous research show that material composition, location, market and material flow, utilization and regulations are the crucial information needed. In terms of material composition, recyclers need information about the material composition of the product, especially the valuable and hazardous substances. However, in the case of the pressure vessel, the material composition is very easy to identify because there are only four standardized types of pressure vessels, it's very easy for dismantlers and recyclers (PV1, VD1) to identify the material composition. In terms of utilization information, it's not influential in pressure vessels since the material recyclability of pressure vessels is not impacted by the utilization condition. In terms of location, it's not crucial for the recyclers of pressure vessels because the local recyclers usually have regular networking and connection with dismantlers, and compared to market information, the location information is not necessarily needed for getting the material inflow.

Aligned with the previous research, the information about material flows and waste streams is the most important in the recycling actions, especially for the Type IV CFRP pressure vessels. Since the recycling market is still growing and there is a need to develop more recyclers, the whole industry must be aware of the rapidly growing volume of EoL Type IV CFRP pressure vessels in the future.

Other crucial information for recycling Type IV CFRP are the design information of the pressure vessels and the high residual value of the material. The high residual value will give dismantlers motivation to supply the EoL pressure vessels to the specialist recyclers and the design information will hugely help the recyclers recover the carbon fibre more efficiently if the winding method is shared with pressure vessel producers.

6 Conclusion

6.1 What are the existing CE strategies in the pressure vessels in mobility applications and why?

For the RQ1 what are the existing circular economy actions of pressure vessels in mobility applications and why? For the Type I pressure vessels, the existing CE actions are recycling and reuse, while the recycling the dominating and only very few get reused. From a regulation aspect, the inspection requirements on the pressure vessel are quite strict, which means that only a limited volume of used pressure vessels is reusable. From the economic side, because most of the EoL gas vehicles are exported, the domestic supply of used pressure vessels is very small so it's hard for customers to find matching pressure vessels. The used pressure vessels also do not have a bigger price advantage compared to the new pressure vessel because the cost of the virgin metal material is comparably affordable while the transaction cost of the used pressure vessel adds extra costs. From a social and organizational norms perspective, the safety concern of the used pressure vessels decreases the acceptance of reusing actions, and the vehicle dismantlers also lack market demand information. From the technical side, the pressure vessels are not designed for durability, and the used pressure vessels are not reusable because the low quality could not fulfil the inspection requirements.

For the Type IV carbon fiber reinforced pressure vessels, the existing CE actions are mainly from pressure vessel producers who reduce the complexity of the material as well as integrate recycled carbon fiber and recyclable resins. Even though the recycling technology innovation has been developed, there is no recycling market and actions so far. From the regulation aspect, the waste treatment requirement is unclear, and the lack of mandatory requirements on circularity leads to unclear responsibility allocation of waste management and circularity promotion. From the economic aspect, the volume of EoL pressure vessels is very small and the volume is hard to predict because the pressure vessel producers are not willing to disclose the data, and the long lifespan of pressure vessels makes the prediction uncertain. All these factors lead to a lack of investment in scaling up the recycling technology and the recycling market does not exist. From the social and origination norms aspect, there is a safety concern and low acceptance of using recycled carbon fiber, and the negative perspective of considering the pressure vessel as waste makes the unwillingness to disclose the production volume. There is also a lack of business cases showing the economic feasibility of using recycled carbon fiber. From the technology aspect, the downcycling of the carbon fiber is still a technology challenge and using the recycled carbon fiber may risk the original design and production of pressure vessels.

On the other hand, there are also many opportunities for recycling the carbon fiber from the used pressure vessel and then utilizing them in manufacturing new pressure vessels. From the regulation side, the upcoming renewed version of the End-of-Life Vehicle Directive and the existing EPR requirements on vehicles require sustainable waste treatment and circularity. From the economic and market aspect, the market of hydrogen vehicles and the pressure vessel is expected to grow rapidly, the growing supply-demand gap of virgin carbon fiber will make recycled carbon fiber an option for pressure vessel producers. The high residual value of the EoL pressure vessel will create economic incentives for collecting and recycling them. From the aspect of social and corporate norms, the usage of virgin carbon fiber leads to a high carbon footprint of the pressure vessels, which will create a negative corporate image for pressure vessel producers. Moreover, the sustainable narrative of the whole hydrogen economy will require the pressure vessel industry to be sustainable since pressure vessel is a critical component in the hydrogen economy. Finally, there are many ongoing technology innovations in solving the downcycling problem of carbon fiber and some of them have already succeeded.

6.2 What are the key actions and the data needs for the actors in the value chain to conduct such CE strategies

For the RQ2, what are the key actions and the data needs for the actors in the value chain to conduct such CE strategies? In the recycling actions for the Type I pressure vessels, the key actors who are directly involved in the material flows are vehicle dismantlers and recyclers while the vehicle producers and public authority are hugely involved in the information flow. The key actions are the dismantling process, and the most critical information is the technology guidelines and regulation requirements on the dismantling process, and the market information about the material inflow and outflow is comparably not critical since the pressure vessel is considered as a scrap. However, technology information such as dismantling guild lines is rarely provided by vehicle producers while the regulatory requirements are accessible.

In the reusing action for the Type I pressure vessels. The key actions are that the dismantlers consider the pressure vessel as a reusable spare part, inspect it to evaluate the reusability of the pressure vessels and then sell it. The critical information in this process is the market information and regulatory information. The market information, especially the demand of the used pressure vessels is the prerequisite for the dismantlers to consider the used pressure vessel as a profitable spare part. The regulation information, especially the inspection requirement works as a protocol for dismantlers to decide the reusability of the pressure vessels. The regulation requires that the manufacturing date of the pressure vessel must be disclosed to help the dismantlers identify its lifespan. However, unlike other studies, the history and utilization information are comparably not that critical since the inspection requirements are the only information needed to decide the reusability of the pressure vessels. Other key actions come from the vehicle owners and workshops, who purchase used pressure vessels instead of new ones. In this process, the market information about the suppliers and the technology information about the used pressure vessels are critical. For the brand-owned workshops and dismantlers, an internal information platform is a channel for exchanging such information, and it's relatively easier to identify the match ability of the demand and supply. For the independent dismantlers, the third-party spare part trading platform is the main channel for information exchange and the identification information is the most needed information to reduce the transaction costs.

In the recycling action of the Type IV pressure vessels, the most critical actions include that the dismantlers sell the used pressure vessels to the specialist recyclers, the recyclers recycle the carbon fiber and sell it back to pressure vessel producers, who decide to purchase the recycled carbon fiber instead of virgin materials. For the dismantlers, the market information, especially the recyclers and high residual value of the pressure vessel is the most critical. For the recyclers, the market information about the material inflow as well as the design information of the pressure vessels are the most critical ones. For the pressure vessel producers who are the end user of recycled carbon fiber, the market information about the material suppliers and the quality information of the recycled carbon fiber is most critical. Considering there are no pressure vessel specialist recyclers on the market so far, there is some other critical information needed for attracting investment and scaling up the recycling market. The growing production and EoL volume of pressure vessels must be recognized, the negative narrative of considering the used pressure vessel as problematic waste has to be changed, and the recycling technology development information needs to be spread out.

6.3 Recommendation for promoting the circularity of pressure vessels by information exchanging

This research identifies the existing circular economy strategies in pressure vessels value chain in mobility application, the information needed for conducting such circular economy strategies and the external influential factors. With the expectation of a growing volume of Type IV pressure vessels, this section will discuss how to improve information sharing in the future and utilize them as a catalyst for promoting circular economy strategies.

As shown in the findings above, the critical actors who are directly involved in the reuse and recycling actions include pressure vessel producers, workshops, dismantlers and recyclers. Even though certain actors like public authorities, vehicle producers and spare part trading websites are not directly involved in CE actions, they are the main source of the information. The critical type of information includes market information about supply and demand, technology information about the lifespan, dismantling manuals, identification and quality, and regulation information regarding the inspection and dismantling regulations.

The market information about the supply and demand is currently shared among the direct actors and the dismantler is the core of the process since they are the direct owners of the used pressure vessels. For the brand-owned workshops and dismantlers, the internal dealer's information-sharing network is used as the main channel for exchanging the demand and supply. For the independent dismantlers and workshops, the market information is shared via the third-party spare part trading platform. The marker demand of the used pressure vessels as spare parts is the prerequisite for dismantlers to sell the used pressure vessels. One suggestion for stimulating the market information-sharing flow is to enhance the search and matching algorithms to help buyers filter suppliers more efficiently. The identification information like the series number should also be shared to facilitate the matching process. The dismantler association could also make a collective effort to advocate the supply and availability of used pressure vessels as spare parts.

The regulation information regarding the inspection and dismantling regulations is shared by the public authority and can be accessed easily. The dismantler association and gas industry organization could help with spreading the regulation information and make it more understandable.

The technical information mostly flows from upstream actors like pressure vessels and vehicle producers to downstream actors like workshops and dismantlers. The lifespan information which is required to be disclosed by regulation is shared by pressure vessel producers. Regarding the dismantling manuals, the brand-owned dismantlers and workshops can easily access them via the internal information-sharing platform, however, the independent dismantlers have comparably less access to such information. The regulation and incentives are suggested to be in place to facilitate information sharing and encourage vehicle producers to include the provision of dismantling manuals as part of CE actions and initiatives.

The upcoming Corporate Sustainability Reporting Directive (CSRD) is considered a regulation motivation for disclosing sustainability-related information (DIRECTIVE (EU) 2022/2464, 2022). It requires corporations to disclose sustainability information in terms of Governance (GOV), Strategy (SBM), Impact, risk and opportunity management (IRO) and Metrics and targets (MT) (EFRAG, 2022b). However, the CSRD does not have direct influence and requirements for corporations to disclose the critical information identified by the study such as market and technology information. The reason is that it requires big corporations to disclose the social and environmental risks they face and how their activities impact people. Therefore, the information disclosure required by CSRD focuses on the sustainable performance of the corporation such as information related to waste, greenhouse gas emissions and pollution(EFRAG, 2022a). The information sharing of the technology and market information only has an indirect impact on promoting circularity, therefore it's not required to be disclosed in CSRD. Therefore, the CSRD could not provide direct regulatory incentives to share the information which is identified by this study.

However, the EPR and ELV have requirements on the information disclosing as well, which have a direct impact on vehicle producers to share the critical information identified by this study. Extended Producer Responsibility on the vehicles has already been in place in Sweden since May 2023, which requires the vehicle producers to share information with downstream actors to promote circularity. Information such as construction of components, dismantling and EoL treatment guidelines and the possibility of recycling and reuse is required to be shared by vehicle manufacturers. Most of the information is identified as critical and needed in promoting circularity in this study. Even though the existing EPR is only covering passenger cars, buses and lorries with a total weight that does not exceed 3,500 kg, an extended scope is foreseen with the upcoming ELV.

Considering there is no business case and pressure vessel specialist recycler so far, the biggest task of recycling Type IV CFRP pressure vessels is to develop pressure vessel specialist recyclers and market. Therefore, apart from the information mentioned above, there is some information which is particularly needed and important to develop the recycling market for Type IV CFRP pressure vessels. The information includes market information, especially the volume of EoL pressure vessels, the development of recycling technology and the economic feasibility of recycling, especially the huge residual value of carbon fiber.

The first critical information is the market, especially the estimated growing volume of the pressure vessels, as well as the EoL volume of pressure vessels, should be shared with all the stakeholders. Even though different reports make different predictions on the development of hydrogen vehicles, the rapid growth is all agreed. U.S. Commercial Service(European Commission, 2024) estimated that there will be 2 million hydrogen vehicles equipped with pressure vessels by 2030, and the amount of pressure vessels is expected to be 4 million. Currently, the low volume, unstable and unpredictable supply of EoL pressure vessels is the biggest concern and barrier to developing the recycling market. The volume information should be provided by the pressure vessel producers as well as the composite association and government. The receiver of the information should be the investors, dismantlers and recyclers. Only after knowing the volume of EoL pressure vessels, the investors will consider it as an investment opportunity and large investment could go into scaling up the recycling capacity and the market for specialist pressure vessel recyclers will be developed. The dismantlers and recyclers will also recognize the material inflows and calculate the economic feasibility of recycling the pressure vessels.

For pressure vessel producers to disclose the volume of their production, the negative narrative of the pressure vessel waste must be changed because it will prevent the disclosure of pressure vessel volume. Instead of considering the huge volume of pressure vessels as waste and environmental concern, the pressure vessel producers should consider them as positive opportunities since the materials could be recycled and used in manufacturing new pressure vessels. To encourage more data disclosure on the volume of Type IV CFRP pressure vessels. The negative narrative of the pressure vessel as composite waste to be minimized and hidden must be converted into the positive narrative of considering them as valuable material because of the recycling technology development (RT). The narrative of waste can be changed into recyclable materials with recycling technology getting more promoted and widely known. The word "waste" can be changed into "opportunity" to make the pressure vessel producers willing to disclose the volume and therefore attract larger investment in scaling up the recycling market (RT). Therefore, communication about the market volume between the pressure vessel producers and potential recyclers is very critical. Moreover, it's also important for the pressure vessel industry to commute with the whole composite ecosystem because other applications can be the end-user of the recycled material from pressure vessels. There is a need to commute the message that the pressure vessel industry is not taking up all the carbon fiber resources, and the recycled carbon fiber could be reused by other composite applications after the first life in pressure vessels. (RT)

The second critical information is the mature development of the recycling technology and technological feasibility of recycling pressure vessels. Even though the technology of recycling carbon fiber from pressure vessels has already been developed, it has not been widely spread and noticed. The story and information about the recycling case should be provided and promoted by the technology innovator, the composite association, information-sharing platform and the government. Only after the recycling technical do ability and feasibility have been widely recognized, the market of pressure vessel specialist recyclers will be developed. The information about the recycling technical feasibility could make more investors, recyclers and pressure vessel producers aware of the technology, and eventually help with scaling up the recycling technology. It could also help pressure vessel producers improve their eco-design to make their products get recycled more easily. The information about the recycling technical feasibility should also be shared with other composite applications sectors since they could also be the end user of the recycled carbon fiber.

The third crucial piece of information is about the economic feasibility of recycling the pressure vessels, which will help larger investments in scaling up the recycling markets. The high residual value of the CFRP pressure vessel as well as the huge demand for carbon fiber for pressure vessels must be recognized by the whole industry. The economic feasibility could be shown and spread by business cases and examples.

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Appendix

Table 0-1 'Key actors, actions points, information need and sources in the recycling action of Type I pressure vessel'

ACTOR (Role)	ACTION	INFORMATION NEEED	SOURCE OF INFO
Vehicle user Workshop Dealer (EoL gas vehicle provider)	Sell the gas vehicle to dismantler	Market information about the dismantlers	Vehicle dismantler
Vehicle dismantler (Used pressure vessel provider)	Receive the gas vehicle	Market information of material inflow	Vehicle users, workshop, dealer Internal knowledge
	Identify Position of pressure vessel	Technical information	Internal knowledge Vehicle manufacturer
	Take pressure vessel out of vehicle	Regulation and safety requirement Dismantling manuals	Governance authority Vehicle manufacturer
	Pipe out gas and open the valves	Regulation and safety requirement Dismantling manuals	Governance authority Vehicle manufacturer
	Sell the pressure vessel to scrap fraction to recycler	Market information of recyclers	Recyclers
Recycler (Pressure vessel material recyclers)	Receive the pressure vessel from dismantler	Market information of material inflow	Dismantler
	Material recycle the pressure vessel	Regulation and safety requirement Technical information	Governance authority Pressure vessel producer Internal Knowledge
	Sell the recycled material	Market information	Material user

Table 0-2 'Key actors, actions points, information need and sources in the reuse action of Type I pressure vessel'

ACTOR	ACTION	INFORMATION NEEED	SOURCE OF INFO
Vehicle user Workshop Dealer (EoL gas vehicle provider)	Sell the gas vehicle to dismantler	Market information of dismantler	Vehicle dismantler
Vehicle dismantler (Used pressure vessel provider)	Receive the gas vehicle	Market information of material inflow	Vehicle users, workshop, dealer Internal knowledge

	Identify Position of pressure vessel	Technical information	Internal knowledge Vehicle manufacturer
	Take pressure vessel out of vehicle	Regulation and safety requirement Dismantling manuals (technical information)	Governance authority Vehicle manufacturer
	Pipe out gas and open the valves	Regulation and safety requirement Dismantling manuals (technical information)	Governance authority Vehicle manufacturer
	Inspect the lifespan	Lifespan information (technical information)	Pressure vessel producer Governance authority
	Inspect the quality and decide the reusability (visual check without leakage check)	Inspection guidelines (regulation)	Governance Authority
	Sell the reusable pressure vessel	Market information	Trading websites Dealer network
Gas vehicle user, Workshop (Used spare part pressure vessels end user)	Search for the used pressure vessel	Market information	Dismantler Trading website Dealer network
	Match the pressure vessel with demand	Quality information Identification information (technical information)	Dismantlers
	Quality check, including leakage check	Quality information (technical information) Inspection guidelines (regulation)	Dismantlers Governance authority
	Install the spare part	Technology information Regulatory	Governance authority Vehicle producer

Table 0-3 'Key actors, actions points, information need and sources in the recycling action of Type IV pressure vessels'

ACTOR and roles	DECISION	TYPE OF INFO NEEDED	PROVIDER
Pressure vessel Producer (end user)	Use recycled carbon fiber from used pressure vessels	Material quality Cost Market information of supplier	Pressure vessel recyclers
	Design pressure vessel in less complex and easy to recycle way	Recycling technology	Pressure vessel recyclers Internal knowledge

		Eco-design knowledge	
Dismantler (material supplier)	Receive the gas vehicle	Market information of material inflow	Users, workshops, dealers
	Dismantle gas vehicle and take out the pressure vessels	Dismantling manuals Regulation requirements	Vehicle manufacturer Regulation Authority
	Sell pressure vessel to pressure vessel specialist recycler	Value of the pressure vessels Market of recyclers	Pressure vessel producer
Pressure vessel specialist Recyclers (technology provider & material supplier)	Receive used Pressure vessel	Market of the material inflow	Dismantler
	Recycle pressure vessel	Recycling technology Design of the pressure vessels	Internal knowledge Pressure vessel producer
	Sell the recycled carbon fiber to end user	Market of end users	Pressure vessel producer