VILNIUS TECH
Vilniaus Gedimino technikos universitetas

Tadas RADAVIČIUS

ASSESSMENT OF CIRCULARITY CONSTRAINTS IN THE EUROPEAN UNION'S SOLAR PHOTOVOLTAICS SUPPLY CHAIN

DOCTORAL DISSERTATION

SOCIAL SCIENCES,
MANAGEMENT (S 003)

Vilnius, 2025

2025-018-M

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The doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2020–2025.

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The dissertation will be defended at the public meeting of the Dissertation Defence Council of the Scientific Field of Management in the *Aula Doctoralis* Meeting Hall of Vilnius Gediminas Technical University at **10 a.m. on 15 May 2025**.

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A notification on the intended defence of the dissertation was sent on 14 April 2025. A copy of the doctoral dissertation is available for review at the Vilnius Gediminas Technical University repository https://etalpykla.vilniustech.lt and the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

Vilnius Gediminas Technical University book No 2025-018-M

https://doi.org/10.20334/2025-018-M

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Tadas RADAVIČIUS

ŽIEDINIŲ APRIBOJIMŲ VERTINIMAS EUROPOS SĄJUNGOS SAULĖS FOTOVOLTIKOS TIEKIMO GRANDINĖJE

DAKTARO DISERTACIJA

SOCIALINIAI MOKSLAI,
VADYBA (S 003)

Vilnius, 2025

Disertacija rengta 2020–2025 metais Vilniaus Gedimino technikos universitete.

Vadovas

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Disertacija bus ginama viešame Vadybos mokslo krypties disertacijos gynimo tarybos posėdyje **2025 m. gegužės 15 d. 10 val.** Vilniaus Gedimino technikos universiteto *Aula Doctoralis* posėdžių salėje.

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Pranešimai apie numatomą ginti disertaciją išsiųsti 2025 m. balandžio 14 d.

Disertaciją galima peržiūrėti Vilniaus Gedimino Technikos universiteto talpykloje https://etalpykla.vilniustech.lt ir Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).

Abstract

The dissertation focuses on analysing circularity constraints within a supply chain. The supply chain in this dissertation is defined as a circular supply chain (CSC) that includes materials, components, and end-of-life management of products. The identified research gap is a missing method for organisations to constantly improve circularity in the supply chain. The dissertation aims to propose a circular supply chain theoretical framework model for the continuous improvement of circularity in the CSC. Furthermore, a tool consisting of the sequence of the procedure for identification and assessment of circularity constraints is proposed and applied in the EU photovoltaics (PV) supply chain.

The literature analysis in the first chapter resulted in a list of indicators to measure circularity and the proposition of a CSC theoretical framework. The second chapter proposes a tool for identifying and assessing circularity constraints. It also describes the methods used. The third part of the dissertation provides the results of the methods used. Dissertation tasks include (1) analysing CE principles in supply chains, (2) analysing theories and concepts related to CE in supply chains, (3) developing an indicator system to measure circularity in the supply chain, (4) proposing a circular supply chain theoretical framework model, (5) proposing and applying a tool for circularity constraint assessment, and solution identification in the EU PV supply chain. The dissertation proposed a circular supply chain theoretical framework model that expands the theory of constraints, knowledge management, resource-based view and resource-dependency theories. The research findings reveal how CE-related knowledge, resources, and capabilities impact the EU PV supply chain's circularity potential.

The dissertation findings are a list of circularity constraints within the EU PV supply chain. The constraints range from a fragmented regulatory approach for end-of-life PV module management in each EU member state to industry difficulties in cooperating for circularity purposes. The top priority is the hesitant exchange of information. The hesitant exchange of information also affects the top three constraints: insufficient traceability of photovoltaic modules, poor logistics handling in the reverse supply chain and illegal end-of-life photovoltaic module exports to non-European countries. The recommendations of the dissertation results suggest synchronising the regulatory landscape across the EU member states, standardising end-of-life PV module operators' data sharing for circularity purposes, and implementing a centralised database in the EU to manage all CSC data related to circularity.

Reziumė

Disertacijoje daugiausia dėmesio skiriama tiekimo grandinės žiediniams apribojimams vertinti. Šiame darbe tiekimo grandinė apibrėžiama kaip žiedinė tiekimo grandinė (toliau – ŽTG), apimanti medžiagų, komponentų ir produktų gyvavimo ciklo pabaigos valdymą. Identifikuota mokslinių tyrimų spraga – trūkstama priemonė, kuria organizacijos galėtų naudoti norint nuolat tobulinti žiedinę tiekimo grandinę. Darbo tikslas – pasiūlyti žiedinės tiekimo grandinės teorinės sistemos modelį, skirtą žiediškumui gerinti. Be to, siūloma priemonė – žiediškumo apribojimų nustatymo ir vertinimo procedūros seka, kurią disertacijoje pritaikomą Europos Sąjungos (toliau – ES) saulės fotovoltikos tiekimo grandinėje.

Pirmame disertacijos skyriuje atlikta literatūros analizė leido sudaryti žiediškumo vertinimo rodiklių sąrašą ir pasiūlyti ŽTG teorinę sistemą. Antrame skyriuje pasiūlyta žiediškumo apribojimų identifikavimo ir vertinimo priemonė bei aprašyti naudoti metodai. Trečią skyrių sudaro naudotų metodų rezultatai. Darbo uždaviniai apima: (1) ŽE principų tiekimo grandinėse analizę, (2) teorijų ir sampratų, susijusių su ŽE tiekimo grandine, analizę, (3) rodiklių sistemos, skirtos žiediškumui tiekimo grandinėje matuoti, sukūrimą, (4) žiedinės tiekimo grandinės teorinės sistemos modelio sukūrimą, (5) žiediškumo apribojimų vertinimo ir sprendimų identifikavimo priemonės pasiūlymą ir pritaikymą ES saulės fotovoltikos tiekimo grandinėje. Disertacijoje pasiūlytas žiedinės tiekimo grandinės teorinis modelis praplečia apribojimų, žinių valdymo, ištekliais pagrįsto požiūrio ir priklausomybės nuo išteklių teorijas. Tyrimo rezultatai atskleidžia, kaip su ŽE susijusios žinios, ištekliai ir gebėjimai veikia ES saulės fotovoltikos tiekimo grandinės žiediškumo potencialą.

Disertacijos išvados atskleidžia žiediškumo apribojimus ES fotovoltikos žiedinėje tiekimo grandinėje. Apribojimai yra skirtingų pobūdžių – nuo fragmentiško kiekvienos ES valstybės narės teisinio reglamentavimo, susijusio su eksploatuoti netinkamų saulės modulių tvarkymu, iki žiedinės tiekimo grandinės sunkumų, bendradarbiaujant žiediškumo tikslais. Neryžtingas keitimasis informacija turi įtaką ir kitiems trims didžiausiems apribojimams: nepakankamas fotovoltinių saulės modulių atsekamumas, prastas logistinis aptarnavimas atvirkštinėje tiekimo grandinėje ir neteisėtas eksploatuoti netinkamų fotovoltinių modulių eksportas į ne Europos šalis. Tyrimo rezultatais pagrįstose rekomendacijose siūloma sinchronizuoti ES valstybių narių reguliavimo aplinką, standartizuoti nebenaudojamų saulės modulių operatorių dalijimąsi duomenimis žiediškumo tikslais ir ES įdiegti centralizuotą duomenų bazę, kurioje būtų tvarkomi visi su žiediškumu susiję ŽTG duomenys.

Notations

Abbreviations

BAU – Business as usual (liet. *įprasta veikla*);
BOS – Balance of system (liet. *sistemos balansas*);
CBM – Circular business model (liet. *žiedinis verslo modelis*);
CE – Circular economy (liet. *žiedinė ekonomika*);
CSC – Circular supply chain (liet. *žiedinė tiekimo grandinė*);
EoL – End of Life (liet. *nebetinkami eksploatuoti*);
EPD – Environmental product declaration (liet. *Aplinkosauginė gaminio deklaracija*);
EU – European Union (liet. *Europos Sąjunga*);
EVA – Ethylene vinyl acetate (liet. *etileno vinilacetatas*);
KM – Knowledge management (liet. *žinių valdymas*);
LCA – Life-cycle assessment (liet. *gyvavimo ciklo vertinimas*);
MCP – Materials, Components & Products (liet. *medžiagos, komponentai ir produktai*);
POE – Polyolefin elastomers (liet. *poliolefinų elastomerai*);
PV – Photovoltaic (liet. *fotovoltinė*);
RES – Renewable energy sources (liet. *atsinaujinantys energijos šaltiniai*);
RFID – Radio frequency identification (liet. *radijo dažnio identifikavimas*);
SD – Sustainable development (liet. *darnus vystymasis*);

TOC – Theory of constraints (liet. *apribojimų teorija*);
TOPSIS – Technique for Order of Preference by Similarity to Ideal Solution (liet. *pirmenybės tvarkos pagal panašumą į idealųjį sprendimą metodas*);
TT – Technology transfer (liet. *technologijų perdavimas*).

Contents

Introduction

Problem formulation

The global economy faces the need to transition towards sustainability. Resource scarcity and the necessity to ensure the resilience of countries and regions in the context of climate change are shaping the way organisations are operating. One of the transitions, particularly for business enterprises, requires changes in the management of organisation functions and the way they work with their suppliers and other stakeholders. A method is required to ensure that various organisations establish relevant procedures and processes within the ecosystem of the CE.

Organisations are willing to explore opportunities available in the CE to improve their business competitiveness, find new markets, new business models, etc. However, their capabilities are usually limited by their resources to implement and improve circular processes. It leads to a focus on narrowing down strategies, such as designing out toxic materials, reducing material consumption, etc.

For closing the loop or slowing down strategies, one action within the chain without cooperation with the rest of the players in the ecosystem can lead to limited CE applications. The organisations require cooperation in developing circular processes with their networks to improve the reuse, recycling and repair of materials, components and products. The mainstream approach is for product manufacturers to lead the initiative of developing circular processes. The approach results in focusing on circularity improvement for the product manufacturer, which is not necessarily improving circularity in the rest of the supply chain. Thus, the need arises for a tool for organisations to work within their supply chain to improve circularity step-by-step together with the rest of the ecosystem.

Relevance of the dissertation

In the solar PV industry, where most of the components are produced outside Europe, the need for circularity is crucial. Challenges arise in how to manage the supply chain organisations systematically to improve circularity in the whole supply chain. The dissertation provides a circular supply chain theoretical framework model to improve supply chain circularity. The dissertation also provides a tool for identifying and assessing supply chain circularity constraints.

The EU's PV supply chain has increased in circularity relevance due to the European Commission's proposed regulatory mechanism to support Net-Zero technologies, including PV. The EU's PV industry manufacturing presence is expected to increase from a mere 6 GW of PV module production to 30 GW by 2030, from silicon production to the final product of the PV module. The growth of the industry is supported by incentives within the Net-Zero Industry Act. Those incentives are also related to a circular economy, for example reducing CO_2 emissions. The assessment of circularity challenges allows the EU's PV supply chain to scale up its presence within the EU by considering the CE constraints faced by the supply chain.

Research object

The research object is the assessment of circularity constraints in the European Union's photovoltaics supply chain.

Aim of the dissertation

The dissertation aims to develop a theoretical framework model of supply chain circularity assessment, whose purpose is to improve circularity in a chosen supply chain.

Tasks of the dissertation

The following activities had to be completed to achieve the dissertation's goal:

1. To analyse the literature on circular economy principles in the supply chain.
2. To analyse theories and concepts that contribute to the assessment of circularity constraints within a supply chain.
3. To develop an indicator system to measure supply chain circularity.
4. To propose a theoretical framework model for a circular supply chain.
5. To propose and apply a tool to assess circularity constraints, and identify solutions to the constraints in the European Union's photovoltaics supply chain.

Research methodology

Several methods were applied to achieve the dissertation goal and objectives. A literature review was used to analyse circular economy principles in relation to the supply chain. A literature synthesis was used to propose indicators and a theoretical framework model of a circular supply chain. Semi-structured interviews were employed to gather organisations' inputs on current circularity issues. The interviewees' transcript coding was used to determine categories of circularity constraints. The Delphi method was used to provide weights for the indicators. Structured interviews were used to determine how interviewees' perceptions of circularity constraints impact indicators. Finally, the TOPSIS method was used to prioritise circularity constraints based on their impact on circularity.

Scientific novelty of the dissertation

With the dominant research approach of focusing only on one or a few organisations, the proposed way looks at management practices at the supply chain level. The dissertation proposes a circular supply chain theoretical framework model in which all of the CSC organisations participate to improve the circularity constantly. The model novelty is reflected by considering CSC as a never-ending process to identify the constraints that limit the growth of circularity.

The dissertation proposes an indicator system to measure circularity within a supply chain. A proposed tool that uses indicators and collects CE constraints from the supply chain organisations results in identifying the most relevant CE constraint. The indicator system is novel as it includes two new indicators in the research field to (1) measure whether the circularity constraints have impacts on the organisation's performance and (2) if there is an interest for the organisation to collaborate in solving the constraint. In combination with the TOPSIS method, a decision can be made on which constraint is the most relevant to solve for circularity purposes. The proposed tool contributes to the management field by systemising supply chain-level information to generate a list of circularity constraints and assessing their impact on the supply chain.

The dissertation contributes to the management field by expanding the theory of constraint application beyond the production environment to look for constraints that limit circularity in a given industry supply chain. Each stakeholder group is presented within the supply chain stages, from material producers to recyclers. The dissertation results demonstrate that for a successful improvement of a circular economy system within supply chains, the collaboration of stakeholders in determining constraints and their impact is essential. The dissertation results also demonstrate that CSC organisations, from a resource-based view and resource-dependency theory, in combination with knowledge management theory, are limited with resources, information and capabilities to improve circularity even at the organisational level, as they are dependent on other organisations.

Practical value of the research findings

The findings of the dissertation demonstrate a list of circularity constraints within the EU's PV supply chain. The provided tool facilitates government officials' & organisation managers' capabilities to identify circularity constraints.

The dissertation findings were used to develop a project concept RETRIEVE for Horizon Europe, which received funding from the European Union's Horizon Europe Research and Innovation program under grant agreement No 101122332 (Reintegration of photovoltaic panel waste back into manufacturing as high-value products, n.d.).

The dissertation results were also used to provide feedback for the National Audit Office of Lithuania to develop an assessment topic, "Readiness to utilise waste from solar and wind power plants and energy storage installations" (liet. *Pasirengimas saulės ir vėjo jegainių, energijos kaupimo įrenginių atliekų utilizavimui*).

Defended statements

The following statements are defended in this dissertation:

1. A system of circular economy indicators is proposed to measure the impacts of supply chain constraints on circularity.
2. A theoretical framework model is proposed to assess the performance of supply chain circularity.
3. A tool is recommended to assess circularity constraints and identify solutions for the constraints.

Approval of the research findings

Five scientific articles have been published on the topic of the dissertation. Two publications were published in a scientific journal included in the *Web of Science* Science Citation Index Expanded, two articles were published in other international peer-reviewed journals, and one article was published in peer-reviewed international conference materials.

The author has made four presentations at national and international scientific conferences:

- International Scientific Conference *Contemporary Issues on Business, Management and Economics Engineering*, 13–14 May 2021, Vilnius, Lithuania.
- International Scientific Conference *Business and Management 2023*, 11–12 May 2023, Vilnius, Lithuania.
- International Scientific Conference *40th European Photovoltaic Solar Energy Conference and Exhibition*, 18–22 September 2023, Lisbon, Portugal.
- International Scientific Conference *41st European Photovoltaic Solar Energy Conference and Exhibition*, 23–27 September 2024, Vienna, Austria.

A research internship was completed during the doctoral studies:

- Bern University of Applied Sciences, Biel, Switzerland, in 2023.

Structure of the dissertation

The dissertation is structured in the following sections: introduction, three main chapters (Annex A), general conclusions, references, a list of the author's publications on the topic of the dissertation, and annexes. The total scope of the dissertation is 160 pages, excluding appendices, with 187 references.

1

Theoretical approach to the circular supply chain: theories and concepts

The chapter focuses on reviewing research works on what circular economy is, defining the role of the supply chain in the transition to a CE, reviewing CE strategies, reviewing theories and concepts affecting the circular supply chain, reviewing factors and indicators affecting CSC, and, lastly, proposing a CSC model. The main research findings of this Chapter are published in the author's two publications (Radavičius & Tvaronavičienė, 2021; Radavičius & Tvaronavičienė, 2022).

1.1. Circular economy overview

Circular economy, a model of production and consumption, surfaced from ecological and environmental economics and industrial ecology (Ghisellini et al., 2016). Academia and practitioners turned to CE when high production and consumption rates challenged resource scarcity and its impact on climate change. Limited global resources turned recycling, reusing, and using renewable materials and other CE strategies into a mandatory objective for organisations. The alignment with the CE principles requires organisations to adopt circular business model components, such as reverse logistics, and the need to address CE strategies (Geissdoerfer et al., 2020). It enables companies to think of new ideas, products, services, processes, etc., within the context of CE and how to deliver benefits to customers and end-users through a circular supply chain. The circular supply chain objective is to extend a linear supply chain model from production to consumer to ensure the recirculation of materials, components and products. There is a strong requirement for collaboration from organisations networks (supply chains, clusters, innovation networks, local networks, etc.) to develop circular processes that can support and implement CE strategies. The circular process refers to a series of actions to improve circularity through, for example, increasing product recyclability.

The CE aims to decouple value creation from waste and resources by transforming production and consumption systems (Camacho-Otero et al., 2018). Production and consumption systems can be categorised into technical and biological cycles (Gnekpe & Plantec, 2023). Technical cycles cover materials that do not fit into the environment as they are, such as metals, polymers, etc. Biological cycles include elements that can re-enter the environment, such as plants, food, clothes, etc. Furthermore, it can be divided into products or service-based systems. The product system includes the manufacturing and distribution of goods, whereas services correspond to a value for the end-user. The system sizes for analysing circularity can be micro (products and companies), meso (industrial parks and value chains), and macro (cities and regions) (Arranz & Arroyabe, 2023). At the end of all these cases, the need for transformation comes from the physical limitations that a linear system has. Transformation requires companies to engage in sustainable practices, rethink business models, and propose new value for their clients (Suchek et al., 2021). By expanding and reshaping the system, organisations can expand their capabilities to transition towards CE.

CE shares a goal similar to that of the low-carbon economy, which is to reduce the consumption of fossil fuels. Researchers suggest that a mutual connection exists between the two (Xie et al., 2023). In both cases, there is a need to tailor applications of sustainability practices to the conditions where they are applied, to consider resource availability, industrial structures, etc. Components and product innovations are required to achieve circular economy goals, such as increasing recycling and prolonging the lifetime of the materials. Organisations can address these innovations by, for example, setting goals related to CE (Ul-Durar et al., n.d.). It must include knowledge related to circular economy acquisition, stakeholder incorporation and entrepreneurial orientation. Resources and knowledge must be managed by each organisation to develop CE innovations that improve circularity at their organisation and in the rest of the value chain.

Enforcing CE requires policy changes to address barriers which slow down the economy's transition to CE. Barriers include a lack of databases for storing data on materials, components, and products, insufficient regulatory pressure for design for disassembly, inadequate sorting processes, etc., (Oluleye et al., 2023).

Specific and generic policy measures are required, whereas specific can be for sectors and generic – for regions or countries. The generic policy can include a carbon tax that ensures that products with a CO_2 footprint are paid through taxes (Govindan et al., 2023). Additionally, a generic policy approach can promote a shared economy or leasing, which reduces environmental impact compared to buying and owning a product (Ahmed et al., 2023). Other generic policy enforcements can include reporting on specific indicators, such as a global reporting initiative that based its indicators on ISO 26000:2010 (Niyommaneerat et al., 2023). The aim is for the carbon tax to be specific for each sector, similar to how global and other reporting initiatives began to have specific requirements on sectors or industries. Each sector has its specific value chain processes, materials usage, end-of-life management procedures, etc., (D'Adamo et al., 2023). Thus, without going into industry specifics, one cannot maximise circular economy benefits in terms of prolonging product lifetime, decreasing emissions, etc.

To investigate CE in systems, such as country, region, organisation, value or supply chains, etc., identification of its specific barriers, enablers, challenges and drivers is required (Ho et al., 2023). Context needs to be taken for each investigated system to improve specific CE indicators. These indicators can also be specific to the investigated system (Faut et al., 2023; James et al., 2023). Usually, it is much easier for organisations to improve efficiency, such as reducing Scope 1 emissions, reducing materials consumption, etc., compared to prolonging the lifetime of materials, components and products or recyclability indicators (Stucki et al., 2023). Circularity strategies that include recycling, reuse, etc., require multiple organisations to collaborate. In these cases, a larger system approach needs to be taken. Within this dissertation, the circular economy component, "circular supply chain", is the larger system that will be investigated.

1.2. Analysis of circular supply chain

The supply chain is a sequence of processes that leads to the production and distribution of a commodity. Supply chain processes are performed by multiple organisations to provide the final product to the end user. A supply chain within the CE ecosystem is the core part responsible for the current flow of materials, and it can act as an enabler to move towards the recirculation of materials. To be an enabler and have the capabilities to ensure CE strategies, a supply chain needs to extend its list of processes to be a "circular supply chain". The CSC needs to be formed based on the following propositions (De Angelis et al., 2018):

1. Supply chain relationships will change in CSCs, shifting from product ownership towards greater emphasis on leasing and service-based strategies enabled by digital systems.

2. CSC's requirement for structural flexibility and reduced geographic barriers for SMEs and innovators within regional or local loops plays an important role in their implementation.
3. CSCs must consider both closed and open material loops in technical and biological cycles.
4. CSCs are enabled by close supply chain collaboration with partners within and beyond their immediate industrial boundaries, including suppliers, product designers and regulators.
5. Procurement policies in both the private and public sectors are important for the transition to CSCs if the entities go beyond minimum legal requirements to include CE principles.

Said propositions are required to change the mindset from common supply chains towards CE-incorporated processes to convert the supply chain into CSC. De Angelis et al. (2018) suggest that there is a gap between the literature on CE and sustainable supply chain management (SSCM) towards practical implementation in organisations and their supply chains. Sustainable supply chain management covers additional topics beyond CE, such as social aspects. Other researchers, e.g., Batista et al. (2018), suggest the following propositions for defining a circular supply chain:

1. CSCs represent an expansion of the closed-loop narrative of sustainable supply chains in terms of the scope and focus of the value chain systems they consider.
2. CSCs extend the boundaries of closed-loop supply chains by considering post-production stewardship to include forward-feeding flows into alternative supply chains.
3. CSCs support sustainable value chain systems derived not only from products and their EoL returns but also from associated byproduct synergies, services, and waste flow.

Batista et al. (2018) reviewed the literature on different CSC definitions, such as closed-loop supply chain, sustainable supply chain management, and green supply chains, and suggested the following description of the circular supply chain:

"*The coordinated forward and reverse supply chain via purposeful business ecosystem integration for value creation from products/services, by products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organisations*" (Batista et al., 2018).

A CSC involves the reduction of raw materials by providing substitutes that are long-lasting, upgradable, made with renewable energy sources (RES), recyclable, and upcycle (Maranesi & De Giovanni, 2020). Upcycle of materials means that the materials should not lose their quality after the recycling processes and, in the best-case scenario, have higher quality than before. Maranesi and De Giovanni (2020) are not against low-value recycling. Kopnina (2018) argues that downcycle should be avoided based on the cradle-to-cradle approach. The authors' view on the CSC is heavily impacted by the theories related to the CE supply chain. Ogunmakinde et al. (2021) identified the main theories, concepts, and methods that affect the circular supply chain: industrial ecology, cradle-to-cradle, regenerative design, natural capitalism, biomimicry, blue economy, eco-efficiency, eco-effectiveness, reverse logistics, zero emissions, performance economy, permaculture, extended producer responsibility, and material passport. The core connection is that all the topics are related to environmental protection. The core of the CSC is a closed-system supply chain where materials are constantly returned to the industry supply (Cannella et al., 2021). At the same time, CSC is part of the value-added chains approach where the objective is to improve productivity, access to markets, strengthen value chain relationships, increase access to inputs and improve the policy environment (Mossie Birhanu, 2023). The scope of CSC is aimed in the context of a circular economy, which makes CSC more focused on CE objectives.

It is a difficult goal to achieve in the current world where dominant end-of-life (EoL) treatment of materials, components, and products (MCPs) leads to the loss of materials and their quality (Singh et al., 2019). The transition from a business-as-usual (BAU) supply chain towards a circular supply chain requires a shift of organisation strategies, structures, MCPs flows, and collaboration practices between the supply chain actors (De Angelis et al., 2018). These processes are complex and require close cooperation of circular supply chain actors to introduce circular processes.

Various authors attempted to identify barriers, drivers, practices, and challenges of the circular supply chain (Acerbi & Taisch, 2020; Bressanelli et al., 2019; Govindan & Hasanagic, 2018; Iacovidou et al., 2020; Khan & Haleem, 2021; P. Kumar et al., 2021). Table 1.1 shows a summary of the CSC's key focus areas through challenges, drivers, and barriers.

Information sharing difficulty can be solved by technologies such as radio-frequency identification (RFID), 3D scanning lasers, optical character recognition, building information modelling, sensor networks, blockchain, etc. (Iacovidou et al., 2020). Data management enabled by digital technologies allows for optimising CSC solutions and processes (Del Giudice et al., 2020).

The careless behaviour of users can be resolved by enabling product-service systems where ownership of the product is kept by the company (Geissdoerfer et al., 2020). A higher stock of secondary materials can reduce the unpredictability of the market (Eurostat, 2017). With lower uncertainty of secondary materials price, the demand for these materials would possibly increase. Therefore, it would create demand for new scalable high-value MCP recycling processes as the current market demands different quality of materials (Iacovidou et al., 2020).

Table 1.1. CSC challenges, barriers, and drivers (source: adapted from Acerbi & Taisch, 2020; Bressanelli et al., 2019; Govindan & Hasanagic, 2018; Iacovidou et al., 2020; Khan & Haleem, 2021; P. Kumar et al., 2021)

Challenges	Barriers	Drivers
Information sharing between the supply chain actors	Low incentive, minimum awareness of industry 4.0, and the lack of understanding of the importance of sharing the MCPs-related information which is required to achieve CSC processes	Boost in operation efficiency of organisations and allow new business processes for repairing, high-value recycling, etc.
Careless behaviour in product usage	Lack of public awareness	Rise of green product awareness and growth of service-based product models
Entry barriers and low market incentives for repaired, refurbished, second-hand products, etc.	Lack of market regulations and incentives for circular products	Reduced environmental impact by effectively the prolonging life of MCPs
Underdeveloped technologies for end-of-life MCP treatment	High financial investments are required for R&D and the lack of cooperation between supply chain actors to develop new processes	Increase the value of the product and new business activities for region-local organisations
Scaling up EoL processes	Lack of standards, regulations, and policy supports aimed at high-value recycling and other circular EoL processes	Reducing environmental impact and boosting national and regional secondary material stocks
Designing MCPs in a circular way	Lack of cooperation between supply chain actors	MCPs with a longer lifetime are less toxic and more repairable, recyclable, etc.
Logistics to support CSC	Additional costs for reverse logistics introduction	New revenue streams for the organisations to repair, refurbish, reuse, etc., MCPs.

The design of MCPs and business-as-usual logistics adaption for CSC requires cooperation between the supply chain organisations. Even if the processes are created to ensure circularity and therefore introduce repairable, reusable, etc. products, it is still a challenge for organisations to develop successful business models for these products. Khan and Haleem (2021) demonstrated that organisations have a wide range of practices toward solving one or another challenge related to CSC, such as developing a circular culture in the organisation, environmental criteria for supplier selection, etc. The organisations can decide on which circular actions to focus on.

For organisations to prioritise focus on specific areas of CSC, researchers proposed different ways to rank or categorise CSC processes related to MCPs. Cole et al. (2019) attempted to define and rank layers of designing levels and hierarchy:

1. Reduce and conserve materials, design out waste, reduce consumption, and longer-lasting products (highest ranking);
2. Encourage cyclical use of resources and develop incentives to reduce waste;
3. Design products for sustainability and take-back;
4. Reuse;
5. Recycle;
6. Regulate disposal (the lowest ranking to aim for).

The main focus is the designing phases of MCPs, which, if done effectively, can significantly reduce difficulties related to reuse, recycling, and disposal. Varbanov et al. (2021) proposed four main processes for handling EoL MCPs:

1. Waste separation;
2. Material recovery and recycling;
3. Waste-to-Energy;
4. Landfilling.

The enabling condition for these four processes to flourish (except the landfilling) is reverse logistics, as suggested by Varbanov et al. (2021). Reverse logistics are related to the transportation of MCPs between various supply chain actors, such as manufacturers, repairers, users, etc. A new classification of waste is required to adopt CE principles for organisations and countries to account for reused products, higher recycling rates, quality standards for secondary raw materials, etc., (Nikanorova & Stankevičienė, 2020). The need to improve logistics for CSC reverse logistics in terms of tracking, information accessibility, and management of data is evident due to the various conditions of products and their geographical distribution (De Angelis et al., 2018). Reverse logistics category processes involve repair, refurbishment, disassembly, servicing, remanufacturing, recycling, and disposal (Kruczek & Zawartka, 2019). In addition to CSC processes of collection, maintenance, and reuse, CSC enables new business models, such as sharing platforms and products as service models (Kruczek & Zawartka, 2019).

Researchers had different approaches in conceptualising the systems and/or their processes of the CSC. Iacovidou et al. (2020) proposed that CSC is a combination of multiple systems: internal sub-system (processes, actions and values) and external systems (technologies, governance, natural resources, etc.) forming a system of systems. Iacovidou et al. (2020) theoretical system allows the identification and understanding of required changes towards sustainable transition. It is a well-elaborated and defined system that considers cultural and user behaviour influence, policies, values (economic, environmental, etc), business and market activities, technology, innovations, etc. Awan et al. (2021) investigated stakeholder (international organisations, institutions, and suppliers) views related to the interest of concerns, expectations, and strategies towards CSC. The findings show a high interconnection between the organisations towards the success of any supply chain actor strategy or objectives fulfilment. It demonstrates the crucial requirements of cooperation between the CSC actors for achieving goals that have a positive impact on multiple supply chain organisations and users.

In their CSC framework, Geissdoerfer et al. (2018) incorporate circular business models derived from the organisational level. Geissdoerfer et al. (2020) also showcase that the CSC is the interconnection field between sustainable development and CE. Vegter et al. (2020) demonstrated the CSC and circular business model (CBM) from a processes perspective by proposing two levels of processes. Vegter et al. (2020) suggested first-level processes: compose a plan, source, make, deliver, use, return, recover, and enable. The second level consists of more concrete processes, such as planning the supply chain, delivering stocked products, returning defective products, etc. The proposed CSC and CBM system demonstrates the high level of responsibility of organisations in organising and maintaining the mentioned processes.

The CE practical framework standard (BS 8001:2017) for organisations was created in 2017 by a British standards institution (Pauliuk, 2018). Its purpose is to allow any organisation (irrespective of the sector, size, or type) to take responsibility for implementing circular organisation processes. The standard has concrete suggestions for organisations supported by a comprehensive approach but lacks monitoring and measurement of the CSC solutions and development of business models (Pauliuk, 2018). Pauliuk proposed a list of indicators to measure processes circularity related to measuring recyclability, restored materials, quality of materials, etc. Nikanorova and Stankevičienė (2020) proposed a different approach towards the indicator system of circularity consisting of the following groups: waste management, air pollution, and CO_2 emissions, energy, economic opportunities and policy responses, material management, and economic context. The indicators are circular material use rate, trade-in recyclable raw materials, the recycling rate of municipal waste, etc. These indicators are more focused on evaluating the circularity at the country level, but due to their formulation derived from 10R (refuse, rethink, reduce, etc.), they could be adapted at the organisation's level as well. To understand CSC better, further research investigations are suggested to explore topics such as design for circularity, procurement and CSC, CSC collaboration and coordination, circular consumption, product liabilities and producer's responsibility, and CSC enabling technologies (Farooque et al., 2019).

Researchers attempted to apply CSC theories and methods to different industries. Table 1.2 shows four different cases in industries where researchers attempted to improve the circularity of the industry supply chain. Optimisation is an important factor that can allow economically attractive CSC processes. The case study of the truck manufacturer demonstrated that economic benefits can be achieved by implementing an EoL circular process related to components and product repair. Other researchers used mathematical models and scenario modelling to show the theoretical impact of different CSC solutions. Each of the attempts by researchers to improve circularity was limited to only specific circularity processes or only at 1–2 organisations within the supply chain.

Table 1.2. Research related to improving CSC processes (source: made by the author)

Industry	**Research object**	**CSC method applied**	**Results**	**Researchers**
Paper	Case study of the paper manufacturing company	Digitalisation solution to gather information	Unlocked critical decision-making which allowed for improved operational efficiency	(Manavalan & Jayakrishna, 2019)
Forest	Forest value chain	Circular bioprocesses and their output products commercialisation demonstration through a mathematical model	Inputs received by various forest value chain organisations showcased through a mathematical model that for circular processes and their products, economic feasibility and scalability of the processes are crucial	(Ouhimmou et al., 2021)

End of Table 1.2

Industry	**Research object**	**CSC method applied**	**Results**	**Researchers**
Construction	Construction waste processing organisations	Networking theoretical architecture of reverse logistics was created to formulate scenarios based on the intensity of materials recovery through a mathematical model	The most optimal scenario showcases a 24% reduction in the cost of handling construction waste, which includes a higher percentage of waste being recycled compared to the base case	(Ahmed & Zhang, 2021)
Automobile	Truck manufacturer	Process optimisation for spare-parts delivery	Results based on modelled scenarios show economic benefits for a company to operate services for repairing trucks by providing spare parts	(Makarova et al., 2021)

The literature review on CSC demonstrates various practices, methods, and approaches to how organisations are capable of taking responsibility for supply chain improvement towards circularity. Theoretical approaches allow organisations to have a systematic understanding of the interconnection of each actor in the supply chain to overcome challenges for CSC development. Nevertheless, each of the CSCs has its context, which has to be considered. The context includes constraints that limit circularity improvement, with each of the constraints having a different impact. Thus, an approach is missing to identify and evaluate those constraints by involving all CSC actors.

1.3. Review of circular strategies and circular economy implementation approaches

The circular strategy aims to improve organisations' systems so that they become more circular. Circularity strategies can be categorised through the 10R framework, consisting of Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover (Kirchherr et al., 2017). Strategies based on the R principle can vary from a few main ones, such as to Recycle, Reuse, Reduce, or to additional "Rs". From the management perspective, a categorisation of circular strategies allows for identifying participating entities and their roles, allowing the exploration of ways how to manage CE processes.

Refuse, Rethink and Reduce imply the focus on the upstream supply chain. Materials, components, and product producers work primarily alone or in cooperation to achieve these strategies. Reuse, Repair, Refurbish, Remanufacture, and Repurpose include the downstream circular supply chain. The input from the customers or distributors regarding the management of components or products is important for these CE strategies' implementation. The upstream CSC needs to participate by either modifying the product or sharing the knowledge on how to manage the components and products. Recycling and recovery processes are at the end of supply chain activities, where MCPs are processed to recover materials and components. The participation of the upstream and downstream CSC actors, or their non-participation, influences the quality of recycling and recovery. These and other various characteristics of circular strategies imply a high level of complexity. To achieve CE objectives, such as ensuring high-value recycling, cooperation needs to be ensured within the CSC.

Frameworks are being developed by researchers considering different CSC actors, their characteristics, and CE strategy opportunities. The framework suggested by Blomsma et al. (2019) proposes a taxonomy of circular strategies for companies engaged in manufacturing business. The proposed framework allows the creation of a comprehensive understanding of circular strategies and mapping strategies and helps find ways to improve circularity in business. Jørgensen and Remmen (2018) proposed a methodology for analysing CE options for business through redesigning of products, services, infrastructure, supply chain relations, internal business organisations, technologies, etc. They suggest that business is consciously or unconsciously part of five types of networks: value chain, product chain, innovation network, regulatory network, and local network. By analysing the company and its contribution to the network, the framework allows, for example, mapping the baseline through the life cycle, redesigning products and services, etc. The methodology allows the analysis of a single company and provides suggestions for CE improvement.

Parida et al. (2019) propose a two-stage transformation model for large manufacturing companies. The first stage is for the manufacturer (the orchestral of the ecosystem) to conduct an ecosystem readiness assessment (external environment, business model, ecosystem partners). At the end of the first stage of the process, a circularity gap is identified. The second stage includes standardisation, negotiation, and nurturing mechanisms leading to harmonisation of the ecosystem to achieve financial, environmental, and social benefits.

The first approach (Fig. 1.1) is from the standpoint of a manufacturing company for developing circular strategies. The second approach allows the analysis of a single company's circularity potential while considering the networks in which it is involved. The third approach places the manufacturer in the centre of the ecosystem, which is the entity responsible for synchronising the ecosystem of its networks to achieve higher circularity potential. All of the approaches focus on starting the analysis from a particular company and following up with an analysis of their networks to analyse and propose strategies to improve circularity.

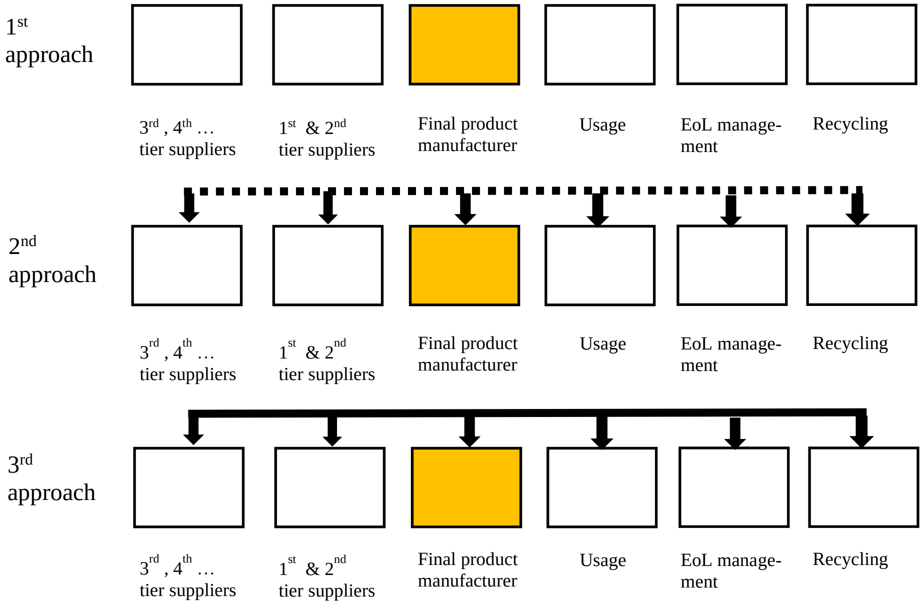

Fig. 1.1. Circularity implementation approaches (source: composed by the author based on Blomsma et al. (2019), Jørgensen and Remmen (2018) and Parida et al. (2019))

The above-mentioned approaches demonstrate how different stakeholders work together during different circular supply chain stages. The work includes agreeing on standards (e.g., calculating emissions or providing documentation on recyclability) or changing materials and component specifications to improve circularity. These approaches place trust in the manufacturer (in most cases) and its interest in developing circularity within its industry-leading role. The possibilities of neglecting the perspectives of other companies in its network (such as recyclers), avoiding long-term CE solutions and focusing only on those solutions that have direct benefits to the manufacturer are present. Looking from the perspective of the network and in the long run, instead of the short-medium term, there is a higher amount of opportunities to be found to improve circularity.

The first approach focuses on one organisation's scope, deciding what circular strategies to focus on, where to invest money, R&D activities, and so on.

Only singular organisation processes are investigated for improvement/creation to support CE strategies. The value that could be captured through a specific CE strategy is chosen and based on the benefits of only one organisation. Knowledge from one organisation only is used to improve CE.

The second approach focuses on one organisation's CE implementation while also considering the networks to which it is connected, such as suppliers and customers. The knowledge is collected and used by the organisation to adapt or implement CE processes. The company can thus select a CE strategy and processes to be implemented while utilising other organisations' knowledge and potentially cooperating with them to achieve a particular CE strategy. The second approach is more collaborative and considers networks and knowledge to facilitate CE implementation strategies to achieve benefits.

In the third approach, one organisation takes the lead for the CE transformation of its CSC. The "orchestrator" organisation sets a common strategy and goals for the rest of the ecosystem. The "orchestrator" bears a responsibility to ensure communication among the ecosystem members, nurture the ecosystem (early investments, setting rules, knowledge-sharing practices, etc.), and negotiate. The negotiation part comes in aligning the activities of the ecosystem (usually the supply chain) to achieve a common goal. Such an approach allows the "orchestra" to influence the ecosystem and achieve a CE-related strategy, which has high value for the "orchestrator".

Each approach has its drawbacks. The analysis of one single company limits capabilities to understand potential changes and impacts of circularity for other relevant stakeholders in the CSC or other networks. Analysis of the CSC through specific circular strategy implementation limits the circularity potential as other potential CE solutions are not being included or evaluated. Both approaches have limitations in including multiple available strategies in terms of circularity and different impacts of potential changes across the industry supply chain. Whole CSC optimisation for CE strategies through marketing, infrastructure development, sales, inbound logistics, etc., of each organisation in the supply chain can allow overcoming barriers particular to CE strategy limitations when focused only on one or several organisations (Awan et al., 2021).

The literature gap within CE applications for organisations is that the approaches of the scientific community and practitioners usually limit the investigation of circularity potential on a large scale. To understand and apply the most suited CE solutions, specific industry CSC companies' circularity status and the potential need to be reviewed through multiple CE lenses. The frameworks and models for analysing companies and their networks rely on placing members of the ecosystem (mainly product manufacturers) who have a high level of influence on its networks. These approaches are placing trust in the manufacturer and its interests in developing circularity within its industry, leading to possibilities of neglecting the perspectives of other companies in its network (such as recyclers), avoiding long-term CE solutions, and focusing only on those solutions that have direct benefits to the manufacturer. The 4th approach for CE improvement in the CSC is proposed based on the discussed first three approaches.

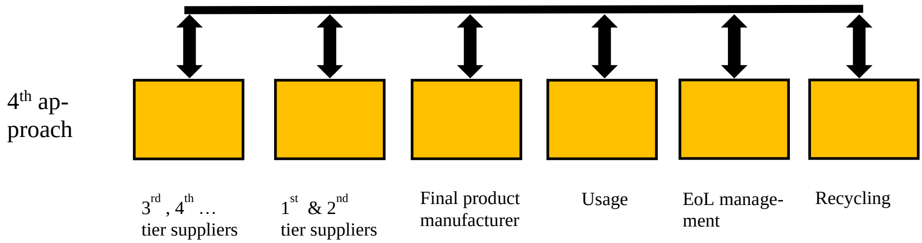

Fig. 1.2. 4th approach for CE improvement in the circular supply chain (source: made by the author)

Figure 1.2 shows that instead of one active organisation taking responsibility for CE implementation within a specific CSC step, all of the organisations are equally involved and active. The arrows indicate knowledge sharing, collaboration, and a co-evolving process where the CSC generates new resources and synergies to enhance performance (Lu et al., 2022). Within the 4th approach, a high level of cooperation degree is required. For a specific industry analysis for CE implementation, all CSC segments must be involved in describing the issues faced, the main constraints and how they can work together to implement solutions. The 4th approach ensures the least possible bias for choosing one or another CE solution as well as maximising the cumulative knowledge of all organisations for CE implementation.

The fourth approach focuses on CE strategy selection and implementation based on the needs of all CSCs instead of one company. Such an approach requires organisations to share their knowledge and resources among themselves to rearrange or develop internal processes at each organisational level. The rearrangement is done with the mindset of sharing benefits and costs to improve the circularity of the entire CSC. The rationale of the 4th approach is to avoid giving power to a single organisation in decision-making by ensuring all of the supply chain stages are represented equally.

The CSC approach for addressing circularity issues allows for an increase in the scope outside of one singular organisation. One organisation can influence other organisations towards circularity improvement. In the case when all of the organisations in the CSC are at the same level in decision-making and sharing their cumulative knowledge, the highest potential for circularity implementation can be reached. Such an approach is intensive in collaboration and knowledge sharing to develop circularity at organisation levels and the CSC level.

1.4. Theories and concepts affecting circular supply chain development

The following sub-chapters will cover theories and concepts that affect the concept of a circular supply chain. The goal is to understand how theoretical implications can be used to assess circularity within the supply chain.

1.4.1. Analysis of the circular economy theories and concepts

The selection of analysed theories was based on whether they had been analysed by other researchers in the field of circular economy within organisations or their networks, e.g., supply chains. Table 1.3 lists the theories and concepts explaining why they were analysed by different authors.

Table 1.3. Analysis of researchers' attempts to employ theories in the context of the circular economy within organisations or their networks (source: made by the author)

Theory or concept	**Purpose**	**Authors**
Sustainable development	To assess China's eco-industrial parks by generating questions based on economic and environmental factors.	Gao et al., 2024
Circular economy	To use a circular economy, proposed strategies related to closing the loop for the creation of a circular supply chain framework.	Amir et al., 2023
System theory	To use system theory to conceptualise the Dutch circular textile transition.	Reike et al., 2023
Networking theory	To analyse circularity resilience through simulations based on organisations' networks.	Massari & Giannoccaro, 2024
Stakeholders theory	To employ stakeholder theory to measure the impact of government pressure and economic incentives on the organisation's movement towards CE practices.	Gallardo-Vázquez et al., 2024

End of Table 1.3

Theory or concept	**Purpose**	**Authors**
Coordination theory	To analyse circular supply chain performance by considering coordination actions through a vertical approach, where the manufacturer leads CSC orchestration, and a horizontal approach, where all CSC organisations participate in improving CSC.	Massari & Giannoccaro, 2023
Resource-based view	To use the resource-based view approach in identifying criteria for selecting suppliers that would improve the circularity performance of the organisation.	Münch et al., 2022
Resource dependency theory	To analyse the risks of adopting circular economy practices based on resource-dependency theory.	Dan et al., 2023
Knowledge management	To analyse the sustainability aspects of eco-innovations and circular economy by utilising knowledge management theory.	Ul-Durar et al., 2023
Technology transfer	To propose a model with 30 criteria for organisations adopting technology transfer to improve circular economy principles.	Ren et al., 2023
Institutional theory	To use institutional theory in proposing circular economy practices for the organisations to choose from.	Hussain et al., 2023
Theory of constraints	To propose a decision-making framework for supply chain resource sustainability.	Koh et al., 2017

Researchers are utilising the above-mentioned theories to either analyse or propose models and frameworks related to circular economy. Each of the theories will be discussed further, and their relation to assessing circular supply chain performance will be analysed.

Sustainable development (SD) theory aims to transform the world's social and economic systems to preserve natural resources. In past decades, tangible targets were developed to achieve this transformation. First were millennium development goals (2000–2015) and recently – sustainable development goals (2015–2030). These goals aim to improve environmental, social and economic dimensions, such as reducing poverty, increasing renewable energy usage, etc. (Shi et al., 2019). Some sustainable development goals overlap with the CE goals, such as reducing emissions by moving away from fossil fuels (Dincă et al., 2022) or reducing waste accumulation (Butt et al., 2023). At the same time, some CE goals, such as refuse and rethink, are not covered by SDGs (de Oliveira & Oliveira, 2023). However, the main focus of CE is the resources and their flow through various systems, whether they are countries, regions, organisations, etc. Their management is the priority for the circular economy. Within the system of a circular supply chain, a sustainable development approach would be to consider social and economic aspects besides environmental impact. Social and economic aspects would result in ensuring there are business cases of circular processes or that these processes would not diminish social aspects of the workforce, stakeholders' well-being, etc. In the end, CE is usually not a standalone goal but a combination of objectives, such as increasing energy independence, mitigating climate change, etc. The contribution of SD within CSC can be concluded as integrating social and economic factors in addition to CE objectives. The possible inclusion of SD into the analysis of CSC would require going beyond circular economy boundaries to explore the social and economic impacts of the circularity constraints.

The **circular economy** is a part of sustainable development. It goes deeper into analysing materials, components, and product flows to understand how they can be managed better. The CE aims to switch from a linear economy that possesses a high accumulation of resource waste. The switch requires following CE principles that are usually referred to as R frameworks, such as reuse, recycle, repair, etc., (Velenturf & Purnell, 2021). These R frameworks need to be further applied in specific systems (regions, organisations, etc.), and indicators need to be identified to measure circularity (Agyekum et al., 2023). Organisations' CE transition means deploying circular business models that incorporate CE principles, such as reducing resource consumption and prolonging the lifetime of the products (Dagilienė & Varaniūtė, 2023). Additionally, changes need to be made by various stakeholders besides organisations, such as government policies and consumption behaviours (Khanna et al., 2022). Thus, CE theory aims to incorporate CE principles into the systems. The outcome should be improved circularity with the identified indicators measuring the transition from a linear to a CE.

Within CSC, the CE is a core principle. CE elements, such as reverse logistics, recycling, etc., need to be present. These circular processes have to be incorporated into the CSC. Some of those processes are costly for one organisation, whereas other organisations can receive value from them through repairable products or a longer lifetime of MCPs. Thus, the possible list of circularity processes needs to be assessed. The assessment needs to consider whether the improved circularity at the organisation level will be continued across the supply chain. As well as whether other supply chain actors are implementing the required changes to ensure that, for example, a recyclable component would still be recyclable after it is integrated into the final product. Furthermore, the recyclers should be ready to identify particular components within a product that are recyclable.

CE is a complex phenomenon. Systems thinking is required to understand CE and apply it in the CSC. **Systems theory** focuses on analysing interconnected processes to understand how the processes are influenced by each other. It originated in 1940 by Ludwig von Bertalanffy, who focused on living systems at that time, whereas now system theory is widely used to analyse various systems (Montuori, 2011). The CE systems theory approach allows for the building of frameworks and models that identify the interconnection between different parts that contribute to CE (De Angelis, 2022). Systems theory is usually used together with other theories, such as stakeholder theory, and if combined with CE, it is possible to use systems theory for analysing identified stakeholders that are related to CE (Demartini et al., 2023). As CE implementation requires the investigation of specifically chosen systems, it is unavoidable to incorporate systems theory elements, as CE is a complex phenomenon involving various parts of the economy.

Multiple organisations are interconnected within the CSC. To ensure the circularity of materials, components, and products, it is unavoidable that the organisations within CSC need to make changes in how they conduct their business. Each of the system parts can influence the circularity, either by improving or blocking it. Thus, systems thinking is essential in analysing interconnections and how parts influence each other. The analysis should reveal the identified issues blocking specific circularity processes, e.g., reusability. Then, the assessment should reveal whether it is worth investing resources in solving specific issues. The decision should be based on whether the issue-solving would have a large impact on circularity performance within the supply chain.

Systems theory emphasises the existence of separate connected parts. In the case of CSC, the organisations provide value and ensure proper resource recirculation. Additionally, external actors impact the CSC system. Within the CSC, an organisation can try not to share its knowledge or make its processes or value delivery limited only to several other organisations in the supply chain, such as its clients and suppliers. However, that is highly unlikely considering the globalisation and interconnection of the organisations. **Network theory** suggests that systems in which organisations participate can be (Dwivedi, 2009) within the value chain, innovation network, regulatory network, local networks, supply chain, and so on. In principle, the network theory analyses how, for example, people, organisations, and groups are structured in terms of their relationships. In these networks, various stakeholders are connected in terms of information (exchange, receiving information, sending information, etc.), activities (innovations and processes), collaboration (policies and standardisation), close business activities (purchase of materials and components and customers), and so on. The value chain in the circular economy's context allows organisations to develop a new value for customers through logistics and support activities like human resources or marketing (Eisenreich et al., 2022). Whereas a circular supply chain is a narrower approach, focusing on the materials, components, and product flows through the supply chain to optimise their management towards enhanced circularity. An innovation network involves other organisations' knowledge, resources, etc., to develop solutions beyond state-of-the-art. The regulatory network covers the system where the organisation is usually dependent on it or can minimally influence how regulatory bodies develop regulations or laws that impact the organisation's activities. Local networks are local suppliers or other organisations in the geographical nearby location that allow organisations to generate value. The supply chain network is the backbone of an organisation's capability to process inputs to create outputs in terms of products or services. A combination of networks is involved in establishing a CSC. Each organisation's supply chain cooperation can improve the competitiveness of the supply chain (Mukhtar & Azhar, 2020). To be competitive in the circularity metrics, the supply chain needs to include other networks, such as local, regulatory, and innovation. The defining process in which networks participate and how they impact the circularity aspects requires the identification of a particular supply chain and its scope. Knowing the networks and their impact on the CSC, circular processes can be developed, optimised, and/or synchronised.

The role of networking theory within the CSC context is to identify the networks that the CSC is a part of and determine whether they have an impact on circularity implementation. Other supply chains, for instance, can be a source of secondary materials. Regulatory networks, entities, and organisations that deal with regulations are impacting how organisations' activities are carried out. Thus, by identifying the networks, such as regulatory, organisations can attempt to pressure the network to make adjustments to the regulatory environment. Singular organisations have a weaker voice rather than a consortium or a group of organisations. Thus, the regulatory network plays an important role in the development of CSC and its circularity potential. Depending on the specifics of CSC, other networks, such as local supply chains, can have a high impact on reducing the costs of circular processes or enabling higher circularity potential. The networks need to be considered because a single CSC cannot be managed without considering the impacts of other networks on the CSC.

Within the network of CSCs, it is important to identify all relevant actors influencing or being influenced by CSCs. **Stakeholder theory** analyses relationships between businesses, groups, and individuals that affect or are being affected by organisations (Parmar et al., 2010). Organisation stakeholders can include clients, employees, owners, etc. External stakeholders affect the organisation indirectly; it can be governments, communities, suppliers, etc. Organisation managers ensure and strengthen the connection with stakeholders to keep them in the loop regarding the organisation's activities and ensure that proper value is delivered and the interests of the stakeholders are considered. This theory aims to identify and manage stakeholders that affect the organisation's activities.

In the scope of CE and CSC, the stakeholder theory provides insights into how to manage multiple organisations. Each of the organisations in the system, such as CE or circular supply chain, needs to be coordinated. It becomes a complex process, considering each organisation's power to influence, interest in influencing, potential threat, or potential to cooperate (Bajaj et al., 2018). Stakeholders are managed by organisations' practices by identifying and managing stakeholder needs, interactions, learning processes between the organisation and its stakeholders, and training (Fobbe & Hilletofth, 2022). Such a process achieves CE-related goals as organisations within the CE ecosystem cannot operate as separate "islands" (Barreiro-Gen & Lozano, 2020). Thus, the objective of the stakeholder theory in the scope of CSC is the mapping and coordination of the stakeholders for the defined goal. Specifically, supply chain organisations should be involved in analysing the issues they face when attempting to achieve specific circular economy strategies.

While some key stakeholders might show high interest in a specific CE process, they might not be willing to participate in the process implementation. Nevertheless, several interested parties can contribute to demonstrating the necessity of implementing the CE strategy and/or overcoming issues related to the CE strategy. The stakeholder involvement improves the power of the CSC to motivate the CSC actors for a cooperation-based approach towards implementing circularity.

Cooperation is necessary for successful CE implementation in CSC. There is a need to have procedures for how two or more organisations can work together towards a common goal. The coordination implies that multiple actors pursue goals together because a sole actor cannot achieve them alone (Malone, 1988). The **theory of coordination** is a body of principles on the coordination of actors' activities. Within the CSC field, coordination is crucial for decision-making in terms of CE-related activities (Agrawal et al., 2022). The principles in the CSC can be related to information sharing, where one organisation's knowledge might be a must for another organisation to implement circular processes (van den Berg et al., 2020). Within the business terms, the contracts of cooperation are usually documented where two or more actors describe how they will work together. When the contracts are made based on ad hoc, for circularity purposes, and both parties agree on how they will work together, those contracts can contribute to the development of a circular supply chain (Raimondo et al., 2021). Thus, a legal indication of how the organisations will conduct their activities is a strong coordination implementation approach.

Organisations must be motivated to solve circularity issues for CE-related cooperation goals to be successful. Three types of motivation can be distinguished: (1) intrinsic (fundamental) and integrated, (2) identified and introjected (unconscious), and (3) external and non-motivated (Rovanto & Finne, 2023). Fundamental and integrated motivation consists of contributing to solving an environmental issue and provoking change towards CE, for example, to ensure the industry is operating on a sustainable basis or creating alternative ways of doing business. Identified and unconscious motivation relates to the availability and low price of second-hand materials and long-term economic well-being. For example, controlling risk to ensure business continuity into the future or achieving competitive advantage from CE. The last motivation, external and non-motivated, highlights a lack of interest towards CE. Some industries' or businesses' fundamental principles oppose CE objectives, such as fossil-fuel-based products or industries. The motivation for CSC to apply circularity processes can be to achieve competitive advantage, ensure a sustainable future for the CSC, control risks, etc. In the cases where CSC organisations could benefit from CE, they should be motivated to improve CSC circularity.

The establishment of cooperation with concrete action points in legal terms generates long-term potential and reduces risks of failure. A coordination theory implies the need for agreement, preferably in legal terms, to ensure organisations would stick to the CE implementation, which is usually a long-term process. Long-term success in CE implementation can be achieved by aligning the motivations of separate CSC organisations.

Two or more organisations coordinate to achieve their goals by utilising their resources. The **resource-based view** analyses the organisation's internal resources and capabilities to deliver products and services to the customers better than the competitors. The output of analysis can allow the organisation to discover its competitive advantage. Resources can be human capital, physical or organisational (Madhani, n.d.). Competitive advantage is based on resources that are scarce, valuable, and cannot be copied or replaced. The usage of the theory leads to organisations creating products and services with reduced costs, developing new business models, or differentiating in other ways in the market. It is essential to determine limits to which standalone organisations can progress in the circular economy. By understanding the limitations, the decision can be made on whether to attempt to work with the rest of the supply chain to progress further in the implementation of circular economy strategies. Otherwise, progress will be limited, and specific strategies might be difficult to implement, e.g., ensuring effective reverse logistic processes.

Resource-dependency theory focuses on analysing the impact of external resources on the organisation (Bhyrovabhotla, 2012). Organisations need to identify which resources are critically important for them to implement specific strategies. The more resources an organisation can access, the more competitive it will be in the market. One way to gain resources in the field of knowledge is cooperation with the supply chain. This type of knowledge formation can lead to knowledge spillover when unintended parties, such as other organisations, use created processes or products.

Sirmon et al. (2011) suggest that the resource-based view approach "orchestration" allows managers to manage the firm's resources to build up a competitive advantage. Authors suggest that resource management is crucial at any stage of the firm's lifetime. Within the context of CE, where collaboration is required not only at the firm's level but also at the level of the whole supply chain, resource management becomes more complex. Instead of different departments within the firm, the orchestrator needs to synchronise and optimise resource usage at multiple organisations to achieve CE implementation in CSC. This approach leads to difficulty in managing those resources as they are located in different organisations within CSC.

To influence or manage its suppliers or other organisations within the supply chain, an organisation needs to have criteria/indicators on which to base its decisions. Within the CE, an important step for achieving circularity is having the right suppliers who can provide additional value from a resource-based view. An organisation can enhance its capabilities for circularity if it has partners that can provide materials or components meeting environmental standards and environment-related certifications, reducing resource consumption and reducing waste generation (Münch et al., 2022). Choosing the right partners or influencing the current partners to adapt or implement higher circularity would allow an organisation to improve its capabilities. On the other hand, if the organisation is not taking action to influence its supply chain or select new partners, the organisation is dependent on them and their capabilities for circularity in terms of circular strategies, synchronisation opportunities to design circular products, etc.

Organisations can cooperate by utilising their internal resources. One of the areas of resources is knowledge that the organisations possess. **Knowledge management (KM)** allows organisations to improve competitiveness by utilising the knowledge to deliver new value propositions for customers, improve processes, create new products, etc. The main two dimensions of knowledge management activities are enablers and processes (Bessant & Francis, 2005). Enabling mechanisms allow knowledge to be shared by individuals, teams, etc. It facilitates knowledge creation, sharing, adoption, and so on. The processes deal with how the knowledge is created, how it is shared, how it is stored, applied, etc. (Santoro et al., 2018). Knowledge management theory revolves around the central focus of the knowledge within the organisation. KM allows an organisation to attain, create, and share knowledge for decision-making and to create business strategies (Ferreira et al., 2018). It can contribute to new business structures and new concepts of management to improve the competitiveness of the firm.

Figure 1.3 shows the main findings of the literature on how KM can impact the CSC and its processes. Knowledge management's impact on organisations' capabilities to develop circular processes can be divided into internal (within the organisation) and external (organisation networks). Organisations can improve the skills and competencies of the employees within the company so that they can perform daily tasks by considering the CE context (Giudice et al., 2020; Belkadi et al., 2020; Ortega-Lapiedra et al., 2019). Managers can develop and improve circular processes by accessing the relevant knowledge within the organisation's network (Ciulli et al., 2020; Kristoffersen et al., 2020). Identifying the relevant knowledge reveals opportunities for adapting or creating new processes within an organisation to address the CE objectives (Wu et al., 2019).

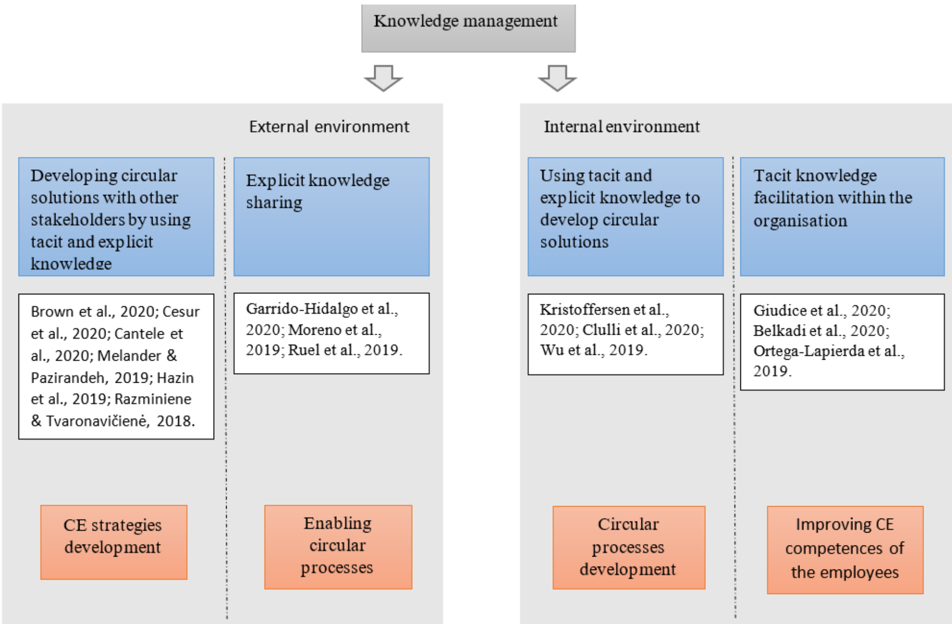

Fig. 1.3. Conceptual framework of how knowledge management impacts an organisation's capabilities to develop circular processes (source: Radavičius & Tvaronavičienė, 2022)

The CE ecosystem involves multiple stakeholders within organisations' networks. Organisations can contribute to knowledge sharing to make other parts of the supply chain more circular (Moreno et al., 2019). New circular processes can be developed by understanding the relevant information that is attributed to specific products or materials (Ruel et al., 2019). It can be supported by ensuring knowledge accessibility for the relevant organisations (Moreno et al., 2019).

The circular processes are linked with various CE strategies, such as reducing materials usage, enabling reparability, etc. The implementation of such CE strategies requires cooperation between multiple stakeholders as it involves complex processes of different organisations. The synergy of organisations' knowledge towards circular process creation, actively sharing knowledge, and participating in KM formation requires close cooperation of organisations and their networks (Brown et al., 2020; Cesur et al., 2020). Trust is required within the ecosystem of managing CE strategies when multiple organisations and their networks are involved (Cantele et al., 2020; Melander & Pazirandeh, 2019). Each of the organisation benefits from the active part of co-creation and sharing knowledge through the creation of their circular solutions within organisations, leading to reduced waste generation, increased materials and products recycling, etc. (Haziri et al., 2019; Razminiene & Tvaronavičiene, 2018).

Organisations' capabilities are improved when they can facilitate tacit and explicit knowledge that is related to CE. By using the knowledge for their business processes and strategies, organisations can develop their circular solutions. Knowledge sharing and cooperation of organisations and their networks must be present to allow and foster CE implementation in other organisations. Within the CE ecosystem, knowledge management of various organisations can lead to the creation of a CSC through the implementation of CE strategies.

Kogut and Zander were among the first to link the knowledge-based theory with competitive advantage (Sazali et al., 2009). The tacit type of knowledge, which is based on people's skills, competencies, know-how, etc., is difficult to transfer. Tacit knowledge can be passed on to another person through socialising. By receiving tacit knowledge through socialising, a person can create new knowledge that could potentially lead to the generation of explicit knowledge. Explicit knowledge, based on software, hardware technologies, documents, procedures, etc., is the core of the **technology transfer (TT)**. Explicit knowledge is easier to transfer compared to tacit knowledge. Tacit knowledge is required to generate explicit knowledge, which can be used by organisations to improve their competitiveness. In the CE ecosystem, explicit knowledge allows organisations to develop strategies and processes to enable CE strategies. In this ecosystem, the roles of technology transfer and transferee are important for establishing CE strategies. Their management through digital technologies could foster progress in adapting supply chains to implement CE strategies.

The impact of technology transfer on organisations' capability to develop circular processes is shown in Figure 1.4. Procedures, white papers, guidelines, physical assets, etc., can be transferred from one organisation to another. Either in academic spin-offs, focusing on a specific technology transfer (low-carbon technology as such), or in other forms, organisations can share explicit knowledge

(Kirchherr & Urban, 2018; Poponi et al., 2020). The acquired specific or adaptable technology to the organisation context allows the transferee to develop its circular processes. To enable scalability and allow various other organisations to acquire relevant technology for CE development objectives, the technology can be acquired through various methods, such as licensing, franchising, etc. It is referred to as conditional transfer, where two parties agree on the technology transfer with specific rules. These transfers differ from one organisation to another by scalability, speed, technologies that are easier to locate through various platforms, etc. (Chen et al., 2020; Guo et al., 2020). Based on the open-source principle, organisations can access freely relevant knowledge on how to repair products, footprints for 3D printing, materials passports, etc. (González-Varona et al., 2020; Unterfrauner et al., 2019). The open-source principles of easy and free-of-charge access allow CE ecosystem stakeholders to use it for CE strategies and circular process development.

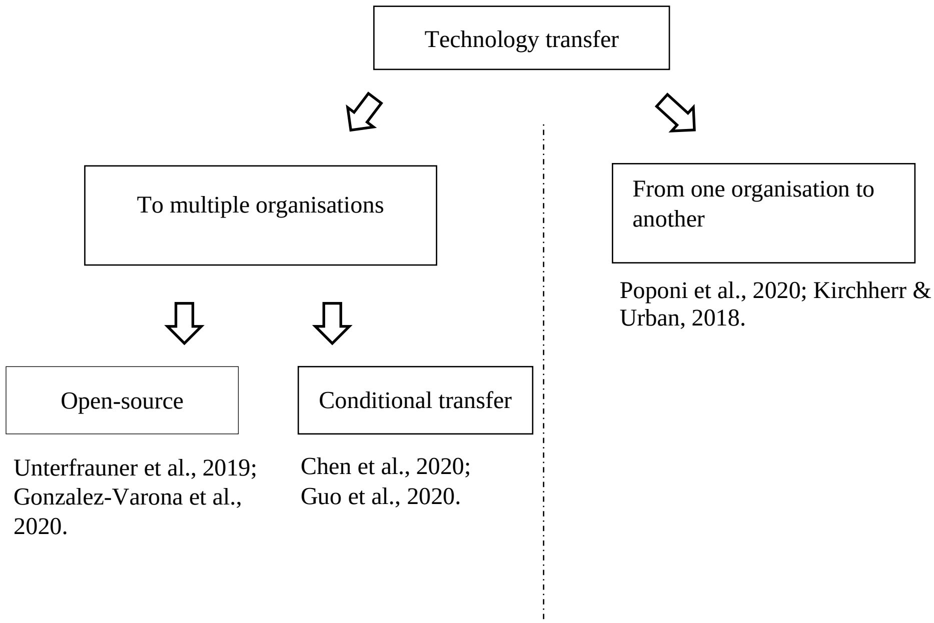

Fig. 1.4. Impact of the conceptual framework of technology transfer on organisations' capabilities to develop circular processes
(source: composed by the author)

Technology transfer within the CE context allows relevant explicit knowledge diffusion among the organisations and their networks. It facilitates the capabilities of organisations to develop new circular processes within their organisations. By allowing the technology to be shared, the CE ecosystem is enriched with explicit knowledge to be used by various stakeholders, which allows CE strategies to be addressed.

Technology transfer and knowledge management overlap in terms of intangible assets. Thus, based on the categories and elements of technology transfer (da Silva et al., 2018), the separation of KM and TT is shown in Table 1.4. Experiences, knowledge, and results of scientific research are the areas of knowledge management. Technical support and logical software are related to specific technical products or processes.

Table 1.4. Distinguishing tangible and intangible assets of TT and KM (source: based on Silva et al., 2018)

Category	**Element**	**Area**
Tangible asset	Tool	TT
	Machine and equipment	TT
	Prototype	TT
	Physical components and device	TT
	Hardware	TT
Tangible and/or intangible asset	Results of scientific research	KM
Intangible asset	Logical software	TT
	Experience	KM
	Knowledge	KM
	Technical support	TT

Technology transfer is important within the CE context to enable or improve opportunities for circular strategies and processes. The technologies in the context of this paper relate to the tangible assets that allow improving circularity: sustainable design of products, components, materials, technologies related to recycling, reuse, etc. Technologies that are developed by the industry or by the innovation network are crucial for CE development. Therefore, TT is included as an additional concept to support KM theory.

The CSC system and its stakeholders need to coordinate resources to develop circular processes. In this process, CSCs are impacted by other networks, organisations or institutions. They impact the way CSC operates. **Institutional theory** analyses organisational practices that are shaped by norms, constraints, shared cognition, structures and social expectations (Arranz & Arroyabe, 2023). Organisations' operations are impacted by institutions and other organisations. Institutional theory analyses isomorphism: (1) how laws and regulations impact organisations, (2) how organisations learn and copy good practices from other organisations, and (3) how organisations follow specific industry guidelines (Hambrick et al., 2004). Within CE, the institutional force of policies shapes organisations' strategies. At the same time, organisations compete with their progress on CE and form good practices. Institutional theory allows for the analysis of the forces outside or within the system's boundary that impact CE. Within the CSC, it corresponds to industry standards, EU or separate countries' regulations, etc. The circularity in the system can be improved by understanding the forces and how they can be managed.

Understanding the CSC system and how it is influenced by external actors provides clarity on steps to be taken to further increase circularity in CSC. Each of the organisations has some processes that deal with waste treatment, recycling, prolonging the lifetime of products, etc. If CE indicators are identified, then it is possible to measure the circularity within CSC. To achieve a desirable result in those measurable indicators, one needs to find solutions how to improve circularity within CSC. The **theory of constraints (TOC)** analyses limitations within the systems, which can hinder reaching specific targets: increasing productivity, having no lack of inventory or materials shortage, avoiding machinery underperformance, etc. (Simatupang et al., 2004). The result of the analysis of those constraints can allow organisations to identify those constraints and find solutions to improve them. Within the context of CE and CSC, cooperation needs are highlighted by the researchers as a key factor in achieving CE strategies. The cooperation constraints that organisations have are as follows (Simatupang et al., 2004):

- Decision-making when considering only the interests of one's organisation.
- A lack of qualitative indicators that would reflect benefits on not one organisation but the whole supply chain.
- Unclear technical changes required to develop a competitive product or service.
- Unclear required changes in supply chain processes.
- Unclear results of one organisation process change impact on the whole supply chain.
- Risk to reduce bargaining power with suppliers.

The constraints can be organisations' practices within the supply chain that prevent the whole supply chain from achieving a particular circularity-related target (Keogh et al., 2017). These types of constraints can limit cooperation's potential to implement CE strategies. Identification of key constraints is an important step towards a cooperation-based approach to the supply chain.

TOC was first introduced within the operational level of organisations. TOC has several steps: identify the constraint (1), exploit the constraint (2), subordinate the process to the constraint (3), elevate the constraint (4) and repeat the cycle (5), finding the next constrained in production processes of organisations (Orouji, 2016). It allowed managers to concentrate on the bottlenecks that limit the improving performance of the production lines. The ultimate goal of TOC is to focus on a particular issue. While other approaches, such as Six Sigma and lean thinking, provide a similar approach, TOC is more focused on the system rather than the problem or the flow (Orouji, 2016).

When considering the whole system, it allows TOC to be used for other applications, not only within production lines. Looking from the perspective of CSC, the scope is inter-connected organisations that deliver products and services to the final consumer while ensuring that closed loops are established. From the CSC perspective, TOC allows identifying focus points within the CSC that are blocking the improvement of circularity, either in specific organisations within the CSC or the whole CSC. Thus, TOC theory allows the whole CSC to be considered in detecting and solving the constraints of CE growth within the CSC.

Table 1.5 provides a summary of each theory and concept through the theory or concept description and relevance to the CSC. The analysis of theories and concepts includes two steps: identification of which aspects of CSC the theory can address and how the theory can contribute to the management of CSC.

Sustainable development is a wide approach to managing organisations and economies in pursuit of social, environmental and economic benefits. The supply chains are required to reflect upon their processes to identify their impact beyond circularity performance.

Circular economy proposes principles to improve resource management. The principles vary, from redesigning materials, components and products to ensuring their recirculation in the supply chains. Organisations are required to adapt their operations to integrate circularity processes that contribute to the objectives of circular principles.

System theory defines each of the element's characteristics and their influence. The CSC can be systemised to identify key elements that are interconnected with each other, e.g., supply chain organisations.

Networking theory implies that organisations and their CSC are part of other networks, for example, other supply chains that receive or can supply recycled materials. The CSC depends on other networks; thus, their management is an important step in CSC development.

Table 1.5. Summary of the theories' impact on CSC (source: made by the author based on a literature review)

Theories or concepts	**Description**	**Relevance to the CSC**	**CSC aspects that theories can help to analyse**
Sustainable development	An approach to develop economies in a manner that benefits the environment, economy, and societies.	Forming CSC while considering economic and social factors.	How is CSC linked with the overall sustainability beyond CE?
Circular economy	The transition of the economy ensures the circulation of resources.	Integration of CE principles in CSC.	Which principles should CSC incorporate?
Systems theory	Analysis of interconnected parts that form a system where all parts influence or are influenced by one another.	Representing CSC as a system where all parts are interconnected.	Identification of system parts and their interconnection in CSC.
Network theory	Participation in various systems where the organisation has a role or is impacted by the network.	Mapping and considering the effects of network actions and organisation effects on the networks from the circularity perspective.	Which networks are relevant for the organisation and its CSC in the pursuit of higher circularity, and how should the networks be managed?
Stakeholder theory	Relevant actors, organisations, etc., that influence or being influenced by the system.	Identification and management of organisations for CE strategies implementation.	Which stakeholders are relevant for the implementation of a particular CE strategy, and how should they be managed?
Coordination theory	Mutual agreements to achieve specific goals.	Agreement of over two organisations for long-term coordination of circularity-relevant activities.	Which of the organisations' coordination needs to be established for circularity purposes, and how it has to be managed?

End of Table 1.5

Theories or concepts	**Description**	**Relevance to the CSC**	**CSC aspects that theories can help to analyse**
The resource-based view and resource dependency theory	Competitiveness through having access to resources and limits to growth due to the resources.	Expanding the opportunities of circular capabilities through access to more relevant resources.	What current resources does the organisation possess for circularity purposes, and what are the limitations that organisations have to achieve higher levels of circularity?
Knowledge management	Knowledge generation, exchange, transfer, etc.	Knowledge to develop/adapt circular processes.	Which knowledge is required for circular purposes, and how can it be acquired or created?
Technology transfer	Explicit knowledge generation, transfer, etc.	Explicit knowledge development and sharing for circularity purposes.	What types of explicit knowledge (materials, procedures, etc.) do organisations need to implement circularity?
Institutional theory	Analysing forces that shape organisations' operations.	Analysing forces that impact CSC organisations' behaviour related to CE implementation.	What types of organisations and what influence do they have on CSCs?
Theory of constraints	Limits to growth or to compete due to the constraints in the organisations' systems.	Pinpointing concrete CE bottlenecks that block specific circularity issues.	What are the constraints for achieving CE strategies within CSC?

Stakeholder theory provides the need to identify the main organisations or actors within and outside CSC that have high importance for CSC developments. The theory covers the CSC aspect of identifying and grouping similar stakeholders, such as product manufacturers. The results of systemically identified and analysed CSC-related stakeholders can be used to identify dependencies and opportunities for stakeholder collaboration for mutual benefits.

The **coordination theory** highlights an element of the agreement, preferably legal, between the organisations attempting to improve circularity. The theory approach allows for improving the chances of long-term success as it binds organisations more tightly to pursue circularity.

The **resource-based view** and **resource dependency theory** allow for the setting of boundaries regarding how much the organisation can work alone in achieving circularity without establishing cooperation. By pooling multiple organisation resources, the circular processes can be developed and maintained within the CSC. The theories allow for the analysis of relevant resources from multiple CSC organisations to be utilised for the common goal of the CSC.

Knowledge management and **technology transfer** conceptualise the role of explicit and implicit knowledge in developing CSC. It revolves around having enough knowledge to develop relevant processes, such as efficient end-of-life collection processes of the products. The aspects of circular economy-related knowledge identification allow CSC to utilise it to develop circular processes.

Institutional theory suggests that organisations are shaped by forces that influence organisations' behaviour. Within CSC, in each of the supply chain steps, the organisations are influencing each other through their operations. The theory allows for looking at those forces to understand their impact on supply chain capability to improve circularity.

The **theory of constraints** allows for focusing on concrete bottlenecks within CSC, how those constraints relate to each of the organisations, and their potential for circularity growth within CSC. These constraints can be identified and assessed by relating them with CE objectives, such as increasing recyclability.

The review of theories and concepts impacting CSC allowed for identifying focus points of the CSC. The identification of CSC issues while considering theoretical solutions (theories and concepts) allows for proposing a solution for CSC management. Each of the theories and concepts provided a specific solution or an approach to CSC handling. For example, the theory of constraints allows for identifying CSC CE-related constraints, the circular economy answers questions related to which objectives within the CE industry CSC should focus on, etc. Based on the generated information, the CSC model can be conceptualised.

1.5. Analysis of circular economy indicators and factors affecting circular supply chain circularity

CE implementation in the supply chain, considering supply chain characteristics, such as focusing on value creation through various organisational activities, is a wide topic. It includes organisations in the supply chain and activities within each of the organisations in the supply chain. The background to building circularity within industries relies on the supply chain organisations that are interlinked with each other to deliver products and services to the customers. The combination of the supply chain network and its results is a complex system of nodes. All of these nodes and processes at each organisation need to be included to optimise the activities and include necessary processes to achieve circularity. All of the organisations within the supply chain need to contribute to changes, such as implementing additional steps in quality control, production process, procurement procedures, etc. These contributions add up to, for example, allowing higher recyclability of the materials, components, and products. Therefore, the difference between a regular linear supply chain and a circular supply chain can be measured by the contributions and results made within the supply chain. Various indicators are available to measure the degree of circularity. Over 256 indicators exist for such measurement (Vinante et al., 2021). Various CE-related indicators at macro, mezzo and micro levels are available, such as regenerative capacity index, carbon balance, water stress, circular use, circular flow, etc., (Nika et al., 2021). The indicators and the factors they measure heavily depend on the system and its related issues. Specific sectors, industries, and the scope of the industry and its supply chain result in the need to adjust or select the right factors and indicators to measure them. Such procedures produced over 100 tools for measuring circularity (ISO 59020, 2022). A wide degree of freedom in selecting indicators and measurement tools based on industry, organisation, and other characteristics increased the green-washing and decreased the relevance of such indicators (ISO 59020, 2022).

Table 1.6 summarises indicators proposed by researchers to measure circularity in supply chains. The indicators focus on materials, components, and products in terms of energy used to process them, amount of materials used, recyclability, waste accumulation, etc.

Table 1.6. Review of supply chain indicators measuring circularity

CE indicator	**Authors**
Energy consumption	(Kurt et al., 2021)
Materials consumption	(Kurt et al., 2021)
Longevity of the product	(Kurt et al., 2021)
Reuse	(Kurt et al., 2021)
Global warming potential	(Calzolari et al., 2022)
Recycled waste	(Calzolari et al., 2022)
Recovered waste	(Calzolari et al., 2022)
Recyclability	(Calzolari et al., 2022)
Ease of disassembly	(Calzolari et al., 2022)
Renewable energy use	(Calzolari et al., 2022)
Water emissions	(Calzolari et al., 2022)
Water use	(Calzolari et al., 2022)
Recycling rate	(Lee et al., 2024)

End of Table 1.6

CE indicator	Authors
Estimated disassembly time	(Lee et al., 2024)
Resource efficiency	(Lee et al., 2024)
Biological materials	(Howard et al., 2019)
Biological materials expected to return to the biosphere	(Howard et al., 2019)

The indicators also tackle materials, components, and products after their usage in terms of whether they will return to the biosphere and whether they will be easy to recycle or disassemble. The indicators focus on materials inflows and outflows in the circular supply chain.

Table 1.7 lists core CE indicators that are present in ISO 59020, which consist of resource inflows and outflows, energy, water, and economic indicators categories. The indicators from the literature are reflected in the ISO 59020 standard, which provides a common practice for measuring key indicators to ensure compatibility between different companies or supply chains.

Table 1.7. Core CE indicators (source: adapted from ISO 59020, 2020)

Category	Circularity indicator	Summary description
Resource inflows	Average % of reuse content of an inflow	Fraction of input material resources that is reused content (except recycled content)
	Average % of recycled content of an inflow	Fraction of input materials resources that are recycled content
	Average % of renewable content of an inflow	Fraction of material resources inflow that is sustainably produced renewable content
Resource outflows	The average lifetime of a product or material relative to the industry average	Indicator of time that an output resource (e.g., product) will remain in use compared to an industry average for the resource
	% of actual reused content derived from an outflow	Fraction of outflow that is/will be reused
	% of actual recycling rate of outflow	Fraction of outflow that is/will be recycled
	% of actual recirculation of outflow in the biological cycle	Fraction of outflow content that is recirculated at the end of life for safe return to the biosphere and meets the qualifying conditions for recirculation

End of Table 1.7

Category	**Circularity indicator**	**Summary description**
Energy	Indicators of energy circularity (inflows and outflows)	
	Average % of consumed energy from renewable sources	
Water	Indicators of water circularity (inflow, outflow, and internal circularity)	
	% of water withdrawal from circular sources	% of annual water demand that is derived from circular sources
	% of water discharged in accordance with circularity principles	% (by volume) of total water withdrawn that is discharged in accordance with circularity principles
	% of water discharged in accordance with circularity principles	% (by volume) of total water withdrawn that is discharged in accordance with circularity principles
	% of onsite/internal water reuse/recirculation	Reuse cycles of onsite water
Economic	Indicators of Economic	
	Revenue share of circular resources (or products)	Total revenue generated per year by use of circular (and/or) non-circular resources
	Material productivity	Revenue generated or total mass of all linear resource inflows
	Resource intensity index	A quantitative measure of economic growth versus total resource use

Resource inflow indicators are reused content, recycled content, and renewable content in the MCPs. The goal is to encourage organisations to use resources that are recycled, already used or are not fossil-based. Recycled content, renewable content and reuse indicators are investigated by the researchers (D'Adamo et al., 2024; Ravikumar et al., 2024). The context of industries where these indicators are applied needs to be analysed. In some cases, indicators might not apply to the specifics of industry materials, components or products.

Resource outflows refer to the average lifetime of MCPs and whether those MCPs will be reused, recycled or can be safely returned to the environment's biological cycle. Energy measures organisation consumption of renewable energy. The water measures water withdrawal, discharge, and re-circularity. Economic indicators refer to revenue shares from circular resources or products, revenue based on resource consumption, and an index representing economic growth versus consumed resources. Longevity, reuse, recyclability and recirculation back to the biological cycle are used by researchers to investigate product circularity (Kusumo et al., 2022; Kowalski et al., 2023).

Various changes in processes are required for organisations and their supply chains to work together to achieve or unlock progress towards the core indicators. On top of that, they are impacted by other stakeholders, such as consumer behaviour through proper recycling of the products by placing the product in the correct bin, regulations, the available quantities of secondary materials in the market, etc. Thus, the dimension of motivation to be an active participant within CSC needs to be explored.

Organisations within CSC can reduce waste generation, reduce costs, and reduce CO_2 emissions, which eventually will lead to higher financial stability (Patra et al., 2024). Reducing dependency on natural resources can lead to increased organisations' competitive advantage (Hussain et al., 2023b). The relevance for the company and interests need to be reflected to determine whether the organisation can benefit from being an active member of a CSC.

Cooperation must have a clear goal which aligns with the organisation's goals and with specific circular indicators. The process ensures that the results of cooperation will have a clear impact on specific CE indicators. Thus, constraints in the supply chain and their impact on specific indicators must be determined. Identifying which constraints would have the highest impact on a particular CE indicator would allow organisations to prioritise the constraints of the highest priority. The focus would be placed on constraints that would bring the highest benefit compared to solving other constraints.

1.6. Proposed theoretical framework model of circular supply chain

The perfect circular supply chain can be envisioned as a fully cooperating CSC that works on implementing the CE strategies. In a perfect scenario, all of the organisations within the CSC are aware of the opportunities of the CE strategies, how much each of the CE strategies requires modifications or adaptations in their activities, and what the benefits and costs are. In that case, all of the organisations would be fully willing to cooperate and share the benefits and costs respectively. Such complexities in each of the supply chains require cooperation to identify the issues and their impacts on organisations' performance. Figure 1.5 presents a theoretical framework model of a CSC. Three elements from analysed theories were taken: **CE knowledge, CE-related resources** and **CE capabilities** to be used for the analysis of supply chain actors to answer the following questions:

1. Which knowledge is required for circular purposes, and how can it be acquired or created?

2. What current resources do organisations possess for circularity purposes, and what limitations do they have to achieve higher levels of circularity?

3. What are the constraints for achieving CE strategies within CSC?

The **CE knowledge** is based on knowledge theory. The theory is employed to analyse supply chain organisations' knowledge, e.g. information relevant to the design of circular products. The knowledge management approach allows for analysing what information organisations possess and what is missing. Furthermore, an analysis can be made of how the information should be acquired and used, as in most cases, multiple actors are required to cooperate to improve circularity within the supply chain.

The **CE-related resources** are based on the resource-based view theory. Organisations seek to achieve competitive advantage by acquiring resources, making them hard for competitors to access. It is essential to determine how far one organisation can improve circularity when only its resources are utilised. If the circularity performance is unsatisfactory, then another approach would be required to work with other networks to increase circularity capabilities.

CE capabilities are based on resource-dependency theory. Cooperation possibilities should be explored when one cannot achieve circularity goals with one's organisational resources. The theory allows for analysing the interconnection of multiple organisations to determine in which cases the cooperation would benefit all of the organisations.

Four steps are proposed to improve the CSC performance: identify CE constraints, assess the impact constraints have on organisations' CE performance, establish cooperation, and solve the constraints. The theory of constraints is used to propose steps on how the assessment of a circular supply chain can be categorised, from identifying the constraint to solving it. The first step is to identify the CE constraints for all supply chain actors. The identification of specific constraints, while considering all of the supply chain actors, allows for generating a comprehensive list of constraints. After the constraints are identified and assessed, cooperation can be established to solve concrete constraints. After the constraint is solved, CE performance is increased. To further improve the CE performance, new constraints need to be identified and solved using the same cooperation approach.

The supply chain consists of 3rd, 4^{th}, … level suppliers, 2nd and 1st level suppliers, product manufacturers, users, MCPs' EoL management, and recycling. **Materials producers** are classified as 3rd, 4th and further suppliers, and **components suppliers** as 1st tier and 2nd tier suppliers. The component producers, or direct suppliers of the material to the component producer, imply a higher connection with the product producer. Meanwhile, further material producers (3rd tier suppliers and beyond) are less bound to a specific supply chain as the materials are less processed for particular supply chain needs (e.g., material quality).

The **product manufacturer** and users are separate actors in the CSC model. The product manufacturer is a significant factor that assembles all of the components for the final product. The **user's** stage involves the actors that deal with the product after it leaves the manufacturer's facility, e.g., the distributors, project developers, customers, etc. **MCPs' EoL managers** stage includes the organisations involved in repairing, reusing, reverse logistics, refurbishment, etc. The **recyclers** stage of the CSC indicates actors that deal with processing the MCPs, for example, into secondary materials.

The objective of a circular supply chain is to ensure the circularity of its materials, components, and products. The objective and stakeholders within the CSC are affected by virgin raw material prices, available subsidies to promote circular processes, etc., (Shekarian, 2020). The main factors relevant to the CSC are networks, stakeholders, and regulatory impacts (Dwivedi, 2009; Parmar et al., 2010; Luthra et al., 2022). The networks are other actors and their supply chains. Due to the nature of CSC, where improving CE performance requires secondary materials, other supply chains can be its source. The stakeholders that impact the CSC are particular organisations, government bodies, or specific organisations in other supply chains that can have a high impact on the performance of the CSC.

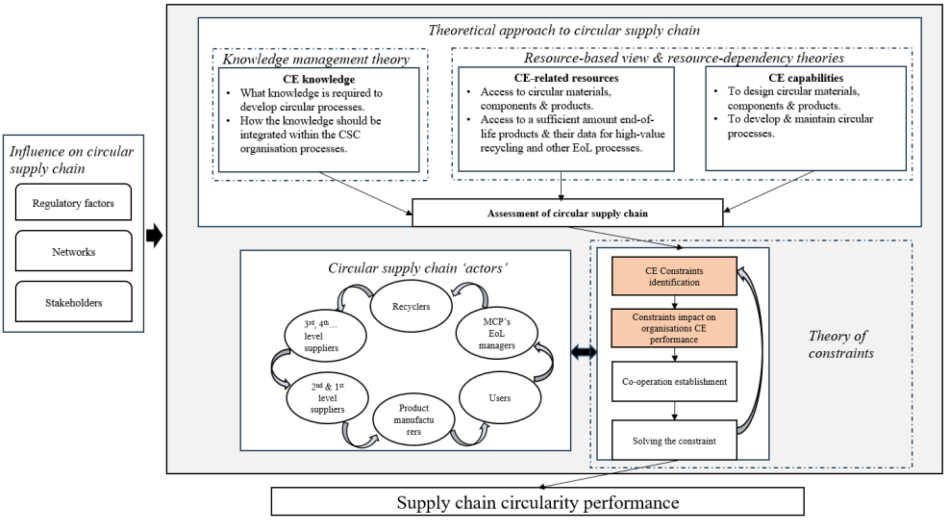

Fig. 1.5. Theoretical framework model of a circular supply chain
(source: made by the author)

The CSC actors solve constraints by collaborating to identify, assess, and solve the constraints. The CSC theoretical framework model allows for identifying the concrete constraints within a particular CSC. Knowing specific constraints is the first step in finding solutions to improving CE performance. The dissertation focuses on the following two processes of the model: **CE constraint identification** and the **impact of constraints on organisations' CE performance**. These processes can be followed by establishing cooperation and solving the constraints. The last two processes focus on implementing solutions to address the circularity constraints identified by CSC organisations.

The theoretical framework model of a **circular supply chain** suggests that each of the actors must work together not only along the way, such as product manufacturers working together with component producers to produce goods for users, but with the whole CSC. It is represented as four processes to identify, assess, establish cooperation, and solve the circularity constraints by working together as a CSC. The system for continuous circularity improvement is affected by the environment, which is represented by regulatory factors, external stakeholders, and other networks. The regulatory landscape can promote or punish the lack of circularity within CSC. The stakeholders impacting CSC, e.g. organisations providing or receiving byproducts of the CSC, are impacting CSC circularity processes. Furthermore, other networks that can constitute a small amount of goods required for the CSC to operate, such as consumables in the production system, impact the CSC's objectives of improving circularity. The proposed model highlights the aspect of including all CSC actors in developing circularity processes that standalone organisations would be unable to achieve due to dependencies on the CSC actors and limited internal resources and knowledge.

1.7. Conclusions of the First Chapter and formulation of the tasks of the dissertation

1. The literature review on CE and circular supply chains suggests that organisations can improve their performance in circularity (increase recycling, reuse, etc.) by cooperating with the CSC actors. The difficulty becomes in managing the CSC actors to achieve circular economy progress by cooperating. CSC is a complex system, as it includes the collection, recycling, reuse, etc., of materials, components, and products. The CSC actors require tools to work together systematically to achieve circularity objectives.
2. CE strategies and their approaches in the research field are primarily focused on a singular organisation's perspective. The selection and imple-

mentation of one organisation's CE objectives, with or without the remaining CSC, has shortcomings in the full CE potential. The difficulty arises in managing the CSC for a common goal where each actor might have different priorities in terms of circularity improvement.

3. Theories and concepts were reviewed to identify theoretical solutions for the implementation of CSC. The most significant finding within the management field, in the context of the circular economy within the supply chain system, is the theory of constraint application. It is followed by a resource-based view and resource-dependency theories to analyse the resources and capabilities of supply chain organisations to improve circularity. The knowledge management theory is considered to analyse what knowledge is required to be utilised by the supply chain actors to work together in improving circularity.
4. The organisation's motivation to participate in coordination within a CSC is to achieve a competitive advantage. A competitive advantage to improve performance in circularity provides a unique opportunity in the CSC. The challenge is to evaluate the circularity constraints within the CSC to prioritise the relevant ones and systematically solve the constraints for continuous improvement of the CSC's circularity.
5. The proposed theoretical framework model for a circular supply chain demonstrates the role of the participation of organisations within the supply chain in solving the constraints. A sequence of processes is required to select the circularity constraints that have the most impact on the CSC. These processes should ensure that the entire CSC participates in identifying and evaluating the circularity constraints.

According to the conclusions of the First Chapter, the following tasks of the dissertation are formulated:

1. To develop an indicator system to measure supply chain circularity.
2. To apply a tool to assess circularity constraints and identify solutions to the constraints in the European Union's photovoltaic supply chain.

2

Methodology of circularity constraint identification, assessment, and selection of the most relevant constraint

The Second Chapter of the dissertation consists of five steps. The first step is to formulate the indicator system, which is based on the proposed circular supply chain model. The second step is to describe methods for the proposed tool, for decision-making regarding constraints on which the EU's photovoltaics circular supply chain should focus to improve circularity. The third step requires a description of the method for collecting CE constraints from the EU's PV CSC. The fourth step consists of a method for collecting inputs from the EU's PV CSC organisations. The last step describes the method to weigh indicators. The main research findings of this Chapter are published in the author's publication (Nyffenegger et al., 2024).

The dissertation aims to use the proposed circular supply chain tool (Fig. 2.1) to evaluate circular supply chain circularity constraints. The tool covers two of the processes within the CSC model: the identification of CSC's CE constraints and the impact of the constraints on organisations' CE performance.

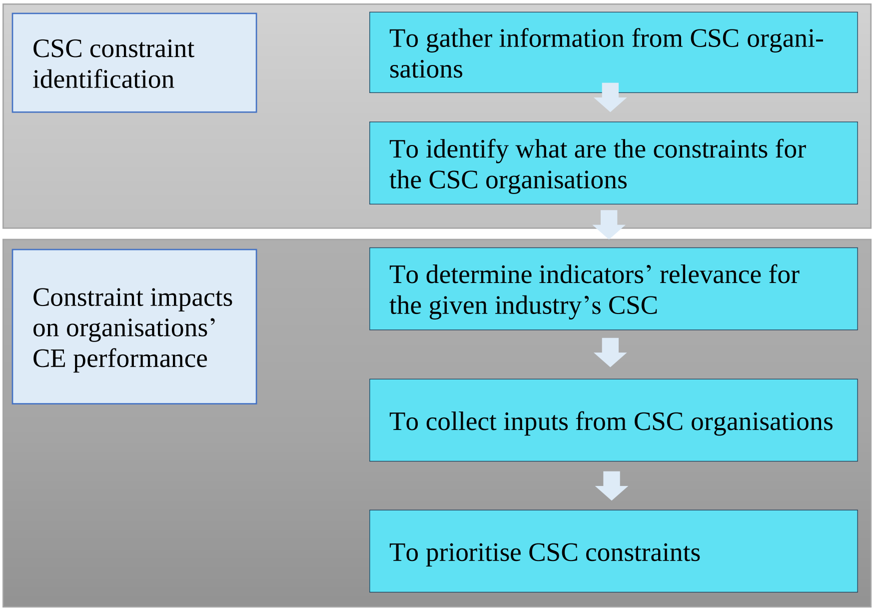

Fig. 2.1. CSC tool for constraint identification and assessment

The tool consists of five steps: (1) to collect data from the organisations, (2) to analyse the data and list the constraints faced by the CSC, (3) to evaluate the indicator's relevance on the selected industry's CSC, (4) to collect inputs from CSC organisations on how they perceive the constraints affecting indicators, and (5) to prioritise the constraints.

The proposed steps should eventually allow for answering the following questions that arise from knowledge management, resource-based view, resource-dependency, and constraints theories:

1. Which knowledge is required for circular purposes, and how can it be acquired or created?

2. What current resources do organisations possess for circularity purposes, and what limitations do organisations have to achieve higher levels of circularity?

3. What are the constraints for achieving CE strategies within a CSC?

2.1. Formulation of circular supply chain tool indicators

The literature review of the circular supply chain, the theories and concepts affecting it, and the main CE indicators suggest the high complexity of the CSC.

Even though organisations are interconnected to provide products and services to the final customer, EoL management, specifically recycling, is often overlooked. The CSC ecosystem is complex and inter-connected, making circular strategy implementation a difficult task.

Understanding constraints limiting CE in circular supply chains requires a clear identification of the main focus points. The focus points are the constraints for moving forward into the circularity for the whole CSC. Each of the organisations has its circularity-related goals that need to be aligned with the rest of the CSC to conduct effective cooperation for addressing specific constraints. Some can focus on recycling, others on increasing recycled content percentage or reducing CO_2 footprint strategies. Thus, a need exists to identify the constraints and evaluate the most promising constraints that would generate the highest benefit.

Based on the literature review, two types of indicators of CE-related constraints are identified: (1) impact on core CE indicators and (2) motivation in solving constraints**.** Indicators that are present both in ISO 59020 and from the literature represent core metrics that could be used in any given industry. The following indicators are used (ISO 59020, 2023):

(1) Reuse the content of an inflow.

A resource inflow is reused content if it has already been used. It can include materials and parts but does not include materials that have been processed through a recycling operation.

(2) Recycled the content of an inflow.

Recycled content includes pre-consumer and post-consumer material. Excluded materials are re-utilisation of materials within an industrial process, such as rework, regrind or scrap generated in a process that can be reclaimed within the same process that generated it.

(3) Renewable (biomass) content of an inflow.

Renewable material is biomass that is replenishable at a rate equal to or greater than the rate of depletion. Biomass material inflows which are technically renewable but are sourced or managed in a manner incompatible with sustainable development should not be considered circular and, thus, as renewable material to calculate this circularity indicator.

(4) A lifetime of MCPs relative to the industry average.

Indicator that identifies the degree to which a resource outflow (e.g., a product or material) can retain its value over time compared to the industry average for that resource.

(5) Reused content derived from outflow.

Calculation of the fraction of content that was recovered or will be realistically recovered from the outflow (at the end of life) for reuse in the production, maintenance, or repair of other resources/products.

(6) The recycling rate of outflow.

The effective level of recovery of materials from resource outflows is obtained through a combination of effective collection and efficient recycling. It is a calculation of the average fraction of content from the resource outflow that was (or realistically will be) recovered and recycled into secondary material for use as a resource inflow to the system in focus or by another organisation or region. The recycled content can be used as a resource inflow, replacing primary materials in the production of new products or for other purposes.

(7) Recirculation of outflow in the biological cycle.

Indicator that calculates the fraction of outflow content (e.g., biomass or nutrients) that is recirculated at the end of life for safe return to the biosphere (biodegradation) and meets the qualifying conditions for recirculation (e.g., composting or anaerobic digestion). The returns to the biosphere can be described as a fully biodegraded material or substance that microorganisms can decompose, and that degrades to organic molecules that living systems can use further, for example, via composting and anaerobic digestion.

(8) Constraint impact on the organisation's CE potential.

Constraint impact on the organisation's CE potential allows for measuring whether solving the constraint will positively impact the organisation. Based on coordination theory, each organisation can have different priorities in terms of circularity. The goals can be to reduce CO_2 footprint, reduce CO_2 emissions, increase recyclability, design out toxic materials, etc. Thus, each organisation's perception needs to be included to identify whether constraint will positively impact their CE goals. Without the linkage between organisations' CE goals and the constraints, it is unlikely that organisations would be motivated to solve the constraint.

(9) Interest in investing resources in solving the constraint.

Interest in investing resources in solving the constraint allows for measuring the organisation's capability to invest resources in solving the constraint. The decision to be highly interested could be dependent on problem-solving requiring little to no resources, few changes in organisation processes, etc. Low interest in solving the constraint could result from its low impact on the organisation, having no priority to invest resources due to the current strategic reasons, having no available resources, etc. By considering a resource-based view, this indicator allows for considering the organisation's current resources in deciding which constraint should be prioritised.

Table 2.1 provides the weighting of indicators and their categories. The sum of all indicator categories provides a priority list based on constraint complexity and its impact on a specific CE indicator and considers organisations' motivation in solving the constraint. Prioritising the constraints is the first key step in establishing CSC cooperation.

Table 2.1. Indicators system for evaluating constraints (source: made by the author)

Indicators	**Explanation**
1.1 Reuse content	Amount of reused components in the product
1.2 Recycled content	Amount of recycled content within the product
1.3 Renewable content	Amount of renewable content (biomass, wood, etc.) in the product
1.4 Lifetime of MCPs	Lifetime of the product
1.5 Reused content from outflow in MCPs	Expected reuse amount of the product at end-of-life
1.6 Recycling rate of MCPs	Recyclability of the product
1.7 Recirculation of MCPs in the biological cycle	The expected amount of product renewable components that decompose in the biological cycle
1.8 Constraint's impact on the organisation's CE potential	Constraint's impact on the organisation's CE performance
1.9 Interest to invest resources in solving the constraint	Organisation's interest in solving the constraint

The tools must be aligned to be used for the specific circular supply chain. Weights for each of the indicators are required based on circular supply chain specifics.

2.2. Selected methods for tool application in the photovoltaics circular supply chain

Expert evaluation is proposed to ensure that the proposed circular supply chain evaluation tool is relevant in the context of the EU's photovoltaics CSC. The multi-criteria decision-making (MCDM) approach will be used to identify the constraint that the circular supply chain should prioritise. MCDM is used to conduct decision-making based on multiple criteria. This approach has been widely used for solving energy problems (Gribiss et al., 2023). The objective is to select the most favourable constraint to be solved by the EU's PV CSC. The alternatives are the constraints that limit circularity improvement in the CSC. The MCDM methods can be classified as (1) multi-objective decision-making (MODM) and (2) multi-attribute decision-making (Kumar et al., 2017). MODM aims to optimise the problem when multiple objectives exist. MADM is used for a singular goal, for example, to rank the best alternative. Based on the 2012–2022 Science

Direct database, articles used the following MCDM methods (top 15) the most (Barretta et al., 2023):

1. AHP in 15452 research articles;
2. Data envelopment analysis (DEA) in 9367 research articles;
3. Fuzzy set theory (FST) in 8730 research articles;
4. Technique for order of preference by similarity to ideal solution (TOPSIS) in 8241 research articles;
5. Goal programming (GP) in 4113 research articles;
6. Case-based reasoning (CBR) in 3258 research articles;
7. FUZZY AHP in 2804 research articles;
8. Elimination et choice translating reality (ELECTRE) in 2782 research articles;
9. Preference ranking organisation method for enrichment of evaluations (PROMETHEE) in 2715 research articles;
10. Visekriterijumska optimizacija I kompromisno resnje (VIKOR) in 2691
11. FUZZY TOPSIS in 2014 research articles;
12. Preference ranking global frequencies in multicriteria analysis (PRAGMA) in 1267 research articles;
13. Simple additive weighting (SAW) in 976 research articles;
14. Multi-attribute utility theory (MAUT) in 948 research articles;
15. Best-worst method (BWM) in 867 research articles.

The most widely used MCDM method (in 15452 research articles) is AHP, followed by DEA (9367), FST (8730) and TOPSIS (8241).

Analytical hierarchy process

The analytical hierarchy process was developed by Saaty in 1980 (Taherdoost, n.d.). The method is used in decision-making when qualitative and quantitative multi-criteria elements are involved. The method involves pair-wise comparison of elements by experts or other respondents, from 1 to 9, where 1 indicates that both elements are of equal value while 9 indicates that one of the elements is much more important than the other.

Data envelopment analysis

Data envelopment analysis was developed by Charnes et al. (2022) in 1978. The method's goal is to evaluate the efficiency or performance of decisions when considering multiple inputs and outputs. Decision-making units must be chosen; they represent the units that are compared. The method allows for identifying best-performing units, identifying inefficient practices, monitoring efficiency, etc.

Fuzzy set theory

Fuzzy set theory is widely used in conjunction with other MCDM methods (Capocelli & De Luca, 1973). The goal of a fuzzy set is to classify objects into multiple categories. The classifications allow for reducing entropy, randomness or bias that is present in MCDM methods. Instead of having criteria evaluated from 1 to 10, it can be narrowed to categories, such as category A consisting of 1–3, category B of 4–6, and category C of 7–10.

Technique for order preference by similarity to ideal solution

The TOPSIS method, developed by Hwang and Yoon in 1981 (Hwang & Yoon, 1981), consists of five steps: (1) construction of a normalised decision matrix containing criteria and alternatives, (2) weighting the normalised decision matrix, (3) determining positive ideal and negative ideal solutions, (4) calculating the distances of each alternative to the positive ideal and negative ideal points, and (5) calculating the relative closeness to the ideal solution (Behzadian et al., 2012). The method is used for decision-making by considering how close alternatives are to the most ideal scenario. The decision-making considers how far the alternatives are from the worst ideal scenario.

The technique for order preference by similarity to the ideal solution was selected in this research to facilitate decision-making. TOPSIS evaluates alternatives and their criteria to select the alternative closest to the ideal solution and farthest from the non-ideal solution. All CSCs usually have to undergo enormous progress to achieve the desired level of circularity, such as 90% recyclability of the product. Since the theory of constraint suggests that resolving one constraint leads to the emergence of new constraints, multiple rounds will be needed to achieve the desired level of circularity in the EU's PV circular supply chain.

The consideration of non-ideal scenario values allows for the selection of a constraint which progresses the indicators more than other constraints. The weighting of the indicators has a high impact on the TOPSIS method as it impacts both ideal and non-ideal scenarios. It can be identified as a weakness of the method (Santolin et al., 2023). In this research context, the relevance of the indicators for a circular supply chain changes based on the progress of the industry, policy environment, etc. Additionally, the weighting of the indicators can be achieved by experts with a very high level of expertise, which the EU's PV CSC organisations experts are lacking due to the low capacity of the upstream supply chain and the lack of organisations in the recycling/reuse field. Experts used for weighting indicators came from either institutes of international organisations working directly with the EU's PV circular supply chain organisations or outside the EU's PV organisations. Thus, the TOPSIS method places higher weight on the experts providing assessment for the indicators and relies less on the EU's PV organisations that lack a high level of expertise.

The Delphi integration with TOPSIS strengthens the methodology by ensuring expert-driven, iterative refinement of indicator weights and criteria evaluations. This is particularly critical given the EU's PV sector's limited upstream expertise and a small number of downstream organisations. By incorporating input from international experts and external entities, the Delphi method mitigates biases and knowledge gaps existing in the circular supply chain, enhancing the reliability of TOPSIS outcomes. The combination of Delphi and TOPSIS offers a robust framework for addressing the unique challenges of the research. While TOPSIS systematically ranks constraints by leveraging objective criteria and their relative weights, Delphi ensures these weights are derived from a consensus among domain experts, reflecting industry relevance and policy dynamics.

TOPSIS application consists of the following steps:

1. Create the decision matrix.

$$(x_{ij})mn,$$

where *m* represents alternatives, *n* is the criteria, and x_{ij} is the intersection of each alternative with the criteria.

2. If needed, conduct the decision matrix normalisation when not all criteria have the same measurement principle.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}},$$

where r_{ij} is normalised numbers and x_{ij} represents positive numbers.

3. Integrate weights in the decision matrix.
4. Identify the worst and best criteria (max–min).
5. Calculate the ideal and non-ideal distances.
6. Perform ratio calculation.
7. Descend the ranking of the alternatives (from 1 to 0).

Weighting is required for the indicators to evaluate their impact on the constraints. The Delphi method, developed in the RAND project by Olaf Helmer, Norman Dalkey and Nicholas Rescher (Weinert, 1999), suggests that groups of experts can be used to provide weights on the criteria. At least four experts are required to ensure that the rating is consistent between the evaluators and that the consensus of experts is achieved with multiple rounds of questionnaires (Pongruengkiat et al., 2023).

Kendall's coefficient of concordance will be used to test whether there is a strong consensus on the criteria weighting. The method was developed by Kendall and Babington (Kendall & Smith, 1939) to assess agreement between experts. The method allows for analysing the consensus or non-consensus of the experts from 0 (no consensus) to 1 (high consensus). The following formula is used to calculate the rank given by all experts to a specific indicator. The first step is to sum up all of the expert rankings for each indicator. Then, the mean is calculated from the sums of each indicator expert's rankings. Afterwards, the following formulas are applied:

$$S = \sum_{i=1}^{n}(R_i - \bar{R})^2,$$

where S is the sum of squared deviations, i represents the indicator, n is the total number of indicators, and R is the rank given by the experts. By knowing S, Kendall's W can be found.

$$w = \frac{12S}{m^2(n^3-n)},$$

where m is the total number of experts. If w is 1, then there is full consensus between the experts, and 0 means no agreement between the experts.

2.3. Selected methods for data collection and indicator weighting

Sub-chapter 2.3 is divided into three parts: identification of the constraints of the EU's photovoltaics circular supply chain (1), collection of the inputs for the indicators (2), and determining weights for the criteria (3). The first part aims to select a method for identifying the constraints within the EU's PV CSC. The second part develops a method for collecting the inputs for the indicators of the proposed tool. The third part determines the weights of the criteria for decision-making.

2.3.1. Identification of the constraints of the European Union's photovoltaics circular supply chain

Semi-structured interviews were used as a data collection method. This interview technique is frequently used in qualitative research (DiCicco-Bloom & Crabtree, 2006; Kallio et al., 2016) because its versatility allows for the exploration of the research questions (Galletta & Cross, 2016). The idea of semi-structured interviews is to explore the research area by collecting similar types of information from each participant (Magaldi & Berler, 2020) without limiting their perception to the scope of a strictly-followed questionnaire (Kallio et al., 2016).

To ensure the validity and reliability of the research results, the initial pool of experts was established. The establishment was based on the following selection criteria: (1) position and responsibilities of the expert within the company, (2) relevance of the organisation's (external) and expert's (internal) contribution towards the CE transition in the photovoltaics circular supply chain (both from a company's and the supply chain's perspective) and (3) the expert's willingness and time to participate in the research study (Bogner et al., 2009; Sourani & Sohail, 2015).

The interviewees were managers of organisations in the upstream or downstream circular supply chain of the solar industry, working in different positions such as chairperson of the board, sustainability and project manager, or research and development (R&D) experts. It should be noted that the interviewees were not necessarily CE experts but needed to be able to understand the CE principles and attributes and to contextualise its potential implementation from a corporate and a supply chain perspective. During the data collection period, the sample of interviewees was steadily expanded through network sampling (Galletta & Cross, 2013). Based on an initial analysis sample of at least ten interviews, the sampling size stopped when the level of data saturation was reached as continuous data collection and open coding produced little or no additional unique code categories (Francis et al., 2010; Ungar et al., 2006). Figure 2.2 shows how unique code categories decreased with each additional interview.

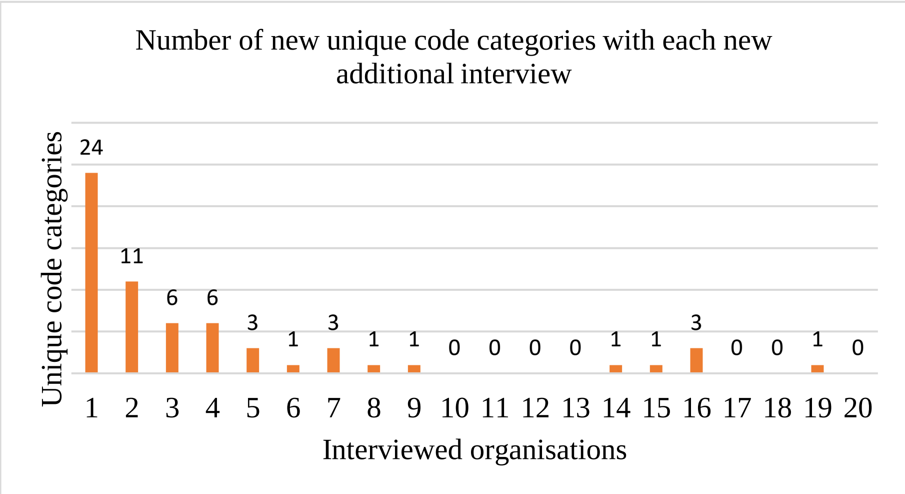

Fig. 2.2. Unique code categories added with each additional interview (source: made by the author)

Following the previously described approach, a total of 20 interviews with representatives from the PV supply chain were conducted. Table 2.2 shows the list of interviewed people.

Table 2.2. Data of interviewed organisations (source: made by the author)

No.	Position	Company	SC phase	Revenue	Company size
A	Sustainability manager	Glass manufacturer	Upstream phase (component)	208 MM	4500 employees
B	Sales manager	Glass manufacturer	Upstream phase (component)	60 MM	< 500 employees
C	Business manager	Front and back sheet producer	Upstream phase (component)	N/A	300 employees
D	PV market manager	Plastics film producer	Upstream phase (component)	88 MM	267 employees
E	Chief operations officer	Solar cell producer	Upstream phase (component)	N/A	19 employees
F	Sustainability manager	Solar cell producer	Upstream phase (component)	13 MM	73 employees
G	R&D engineer	Polysilicon production	Upstream phase (component)	460 MM	1800 employees
H	Chief technology officer	Solar module producer	Upstream phase (product)	5 MM	< 50 employees
I	Chief sustainability officer	Solar module producer	Upstream phase (product)	323 MM	1400 employees
J	Senior climate consultant	Service provider PV installations	Midstream phase (usage)	8 B	3268 employees
L	Chief executive officer	Waste management	Downstream phase (EoL)	6.3 MM	< 25 employees
M	Chief executive officer	Recycling technology	Downstream phase (Recycling)	29 B.	220,000 employees
N	Chief executive officer	Reuse PV trading	Downstream phase (EoL)	< 5 MM	10 employees
O	Project manager	Reuse PV project management	Downstream phase (EoL)	160 MM	1200 employees
P	Consultant for disposal	Service provider EoL management	Downstream phase (EoL)	160 MM	1200 employees
Q	Sales manager	Reuse/Recycling technologies	Downstream phase (recycling)	133.7 MM	532 employees
R	Chief executive	Recycling technology	Downstream phase (recycling)	N/A	40 employees
S	Chief executive	Recycling technology	Downstream phase (recycling)	< 10 MM €	17 employees
T	Chief executive officer	Recycling technology	Downstream phase (recycling)	N/A	N/A
U	Chief executive officer	Recycling technology	Downstream phase (recycling)	N/A	10 employees

The representation of circular supply chain stages is shown below:

- 3rd, 4^{th}, … tier suppliers: 1
- 1st and 2nd tier suppliers: 6
- Product manufacturers: 2
- Usage: 1
- EoL management: 4
- Recyclers: 6

Organisations were categorised into six CSC stages based on their operations. For example, if an organisation produced components for the PV module manufacturer, it was classified as a 1st and 2nd tier supplier. If there were three or more stages between the organisation supplying components or material to PV module manufacturer, the organisation was classified as a 3rd, 4^{th}, … tier supplier.

A semi-structured interview questionnaire was developed, and the questions mainly focused on the managerial perception of barriers, enablers, and goals regarding CE deployment in the photovoltaics circular supply chain. The interview questions are presented in Table 2.3.

Table 2.3. List of questions for semi-structured interviews (source: made by the author)

	Questions
1.	What are your company goals in terms of circularity/circular economy?
2.	Which approaches/concepts did your company already apply to realise the mentioned goals and visions?
3.	Do you have certain cooperation within the company supply chain in terms of CE?
4.	How do you ensure the proper information flow between your company and other stakeholders in the supply chain regarding circularity?
5.	How do you ensure the proper traceability of products/materials?
6.	How do you gather data?
7.	How does data influence decision-making for your company’s circular strategies?

The questions start with the interviewees’ goals related to CE, followed by concepts and approaches that are already applied on the organisational level to realise these objectives. The first two questions allow for initial insights into the participants’ knowledge of CE practices and provide direction for the depth of the interview. The following questions focus on cooperation and information exchange with relevant stakeholders in the supply chain for CE purposes. All interviews were voice recorded and transcribed for the subsequent content analysis. For the data analysis coding, the MAXQDA program was used through a bottom-up approach to identify codes for the constraints that organisations have related to CE performance. The bottom-up approach is a method where code categories are developed over time. Another existing method is top-down, where code categories were already defined.

Most coded constraint categories were categorised. The categorisation depended on the CSC stage to which the interviewed organisations were attributed (Table 2.4). For example, from the usage stage, only three constraints were identified. Eight out of ten constraints were mentioned by recyclers. The categorisation allows for determining if some stages will have issues in providing inputs for constraints that they probably have little to no knowledge about.

Table 2.4. Mapping of constraints based on circular supply chain stages that mentioned them

Nr.	**EU PV circularity constraints**	**3rd, 4th tier suppliers**	**1st and 2nd tier suppliers**	**Product manufacturer**	**Usage**	**EoL management**	**Recyclers**
1.	Unpredictable volumes for reuse and recycling						
2.	Insufficient value chain collaboration						
3.	Insufficient purity of recyclates for reinsertion in PV production						
4.	Uncoordinated legislation over Europe						
5.	Hesitant exchange of information						
6.	Insufficient traceability of PV modules						

End of Table 2.4

Nr.	**EU PV circularity constraints**	**3rd, 4th tier suppliers**	**1st and 2nd tier suppliers**	**Product manufacturer**	**Usage**	**EoL management**	**Recyclers**
7.	Immature recycling methods often result in downcycling						
8.	Illegal PV module exports						
9.	Underdeveloped reverse supply chain						
10.	Conventional PV recycling is not profitable yet						

Upstream CSC might have little knowledge of what happens at the end of the supply chain and the other way around. The table also shows interconnections of constraints, such as unpredictable volumes for reuse and recycling, which is relevant for five out of six CSC stages.

2.3.2. Determination of criteria weights

Table 2.6 indicates a list of indicators that will be used as criteria with the TOPSIS method to conduct decision-making. Alternatives and circular supply chain constraints that need to be prioritised from the CSC perspective to improve circularity were identified. The criteria were weighted by the EU's PV circular supply chain experts. An expert is qualified and has a minimum of two years of work experience in the sustainability field of the EU's PV circular supply chain and three years of experience in the EU's PV CSC.

Table 2.5. List of experts that participated in the Delphi research (source: made by the author)

No.	**Position**	**Organisation**	**Experience in sustainability, years**	**Experience in PV circular supply chain, years**
A	Consultant	Consultancy company	3	22
B	Senior business developer	Research Institute	10	15
C	R&D professional	Research Institute	4	15
D	Deputy managing director	Research Institute	12	23
E	Senior researcher	Research Institute	2	16
F	Executive director	PV association	30	20

The experts used the Delphi method to provide weights and comments for each criterion. Table 2.5 shows the list of experts who participated in two rounds of the Delphi study.

2.3.3. Collection of inputs to the indicators

The sub-chapter aimed to define how the inputs would be collected. Inputs to be used for the indicators in the tool consist of organisations' perceptions of the constraints affecting indicators. The inputs were collected using structured interviews. Due to the need for a rather high level of effort to evaluate the constraints (ten constraints against nine indicators result in 90 inputs), a simple method was chosen by asking interviewees to rate them from 1 (low impact of the constraint on the category) to 5 (high impact of the constraint on the indicator). Organisations were asked minimally to provide inputs on the constraints that are categorised for their CSC stage, a maximum of up to ten. For example, if an organisation was a product manufacturer, they were requested to fill inputs for the 1st, 4th, 7th, 8th, and 9th constraints (Table 2.4).

Table 2.6 provides the required inputs for the indicators. A rating system from 1 (low impact) to 5 (high impact) was used. These inputs represent whether the organisation can have a high impact on the organisation's CE potential if the constraint is lifted. Indicators allow for considering whether the organisation would be willing to pour resources into lifting the constraint.

Table 2.6. Type of inputs for the constraint indicators required from the organisations from each CSC stage (source: made by the author)

Indicators	**Inputs**
1.1 Reuse content	1 (low impact) to 5 (high impact)
1.2 Recycled content	1 (low impact) to 5 (high impact)
1.3 Renewable content	1 (low impact) to 5 (high impact)
1.4 Lifetime of MCPs	1 (low impact) to 5 (high impact)
1.5 Reused content from outflow in MCPs	1 (low impact) to 5 (high impact)
1.6 Recycling rate of MCPs	1 (low impact) to 5 (high impact)
1.7 Recirculation of MCPs in the biological cycle	1 (low impact) to 5 (high impact)
1.8 Constraint impact on the organisation's CE potential	1 (low impact) to 5 (high impact)
1.9 Interest to invest resources in solving the constraint	1 (low impact) to 5 (high impact)

Based on the ongoing EU Horizon project RETRIEVE analysis, up to 50 organisations in the EU are attributed to all the EU's PV CSC stages except for usage (RETRIEVE, 2024). The usage stage consists of thousands of organisations that are mainly installing PV systems. Table 2.7 shows a summary of organisations from which inputs were collected.

Table 2.7. List of organisations interviewed for input collection

No.	**Position**	**Circular supply chain stage (1–6)**	**Experience in sustainability, years**	**Experience in PV circular supply chain, years**
A	Sustainability manager	4	12	4
B	Application developer	2	4	23
C	ESG coordinator	3	3	18
D	Managing director	5	10	10
E	Product developer	4	4	9
F	Managing director	2	9	14
G	Sustainability manager	3	3	3

End of Table 2.7

No.	Position	Circular supply chain stage (1–6)	Experience in sustainability, years	Experience in PV circular supply chain, years
H	Director for strategic marketing	1	4	12
J	Sustainability manager	6	4	4
K	Director	5	11	11
L	Operational manager	6	4	4
M	R&D director	2	5	32

The collection of the inputs is followed after the identification of the constraints from the EU's PV CSC organisations. There are six stages of the circular supply chain. Thus, average scores for each involved stage were calculated. For instance, there might be two or three organisations in the "product manufacturers stage". Their scores need to be averaged to receive the final score for that CSC stage. This process was used for all CSC stages. The total scores in the decision matrix consist of averages from all CSC stages.

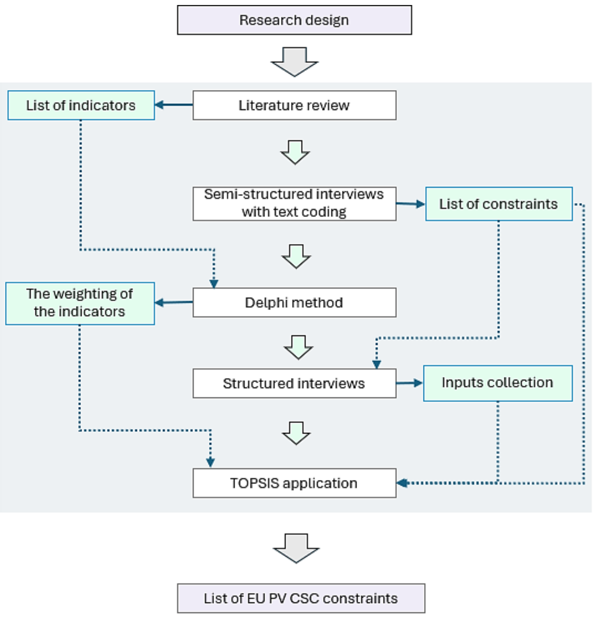

Fig. 2.3. Selected methods and their outputs (source: made by the author)

A summary of all selected methods is shown in Figure 2.3. Literature synthesis was used to develop a list of indicators to measure circularity constraints. Semi-structured interviews and text coding were selected to identify CE constraints that are present in EU PV CSC organisations. The Delphi method was selected to determine the relevance and weights of the indicators specifically for the EU's PV CSC. Structured interviews were selected to collect inputs from the EU's PV CSC organisations on how they perceive CE constraints affecting selected indicators. The TOPSIS method was selected to conduct decision-making by considering constraints, indicators, and inputs from the EU's PV organisations.

All of the selected methods are either qualitative (literature synthesis, semi-structured interviews, structured interviews, Delphi, TOPSIS) or mixed (text coding). The text coding method allows for data generation to analyse generated constraints and their relevance in terms of how many times specific constraints were mentioned.

2.4. Conclusions of the Second Chapter

1. Indicators to assess circularity within the EU's photovoltaic circular supply chain were chosen based on a literature review and ISO 59020 standard, with two additional indicators reflecting organisations' motivation. The indicator system is required to understand how the constraints are affecting specific indicators of circularity. For this objective, the inputs from CSC were required to understand how they perceive the constraint impacts on circularity.
2. The TOPSIS method was used for decision-making to select the most relevant constraint that limits the EU's PV circularity. TOPSIS considers the ideal situation and the worst ideal situation. This means that the experts that provide weight for the indicators have a high impact on the final score, as they influence final ranking by worst-case and best-case ranking values. The EU's PV CSC has a weak presence in the EU as most of the chain is outside the EU. The method gives more power in decision-making impacts to non-CSC industry experts who possess a high level of experience in the industry through PV associations or institutes that work directly with the EU's PV CSC.
3. The EU's PV CSC constraints were identified using the text coding method. Semi-structured interviews were used to interview 20 organisations. MAXQDA program transcripts of the interviews were coded to categorise circularity constraints, goals, and enablers. The methods combination of semi-structured interviews and transcript coding findings revealed that almost all of the constraints were faced by more than two

organisations from different CSC stages. This indicates a clear need for CSC to cooperate in solving constraints, as multiple organisations can benefit from lifting them.

4. Perception-based inputs were collected from the EU's PV organisations. The inputs were based on the evaluation of constraints on a scale from 1 (very low impact) to 5 (very high impact) using indicators. The method findings revealed that the number of constraints and indicators must be limited; otherwise, too many inputs are required from organisations to be requested. Ten constraints and nine indicators produce 90 inputs that should also be supported by qualitative reasoning as to why a specific input was provided by the organisations. The interview duration of up to one hour limited the method for incorporating the higher number of constraints. However, it was sufficient to tackle up to ten constraints to understand their impacts on the EU's PV CSC performance.
5. The weighting of the indicators was done using the Delphi method. Kendall's W coefficient was used to determine if experts had an agreement on the weights of the indicators. Six experts were used for the Delphi study. The findings reveal that multiple rounds were required to align the understanding of each expert, specifically to clearly understand the proposed indicators' meaning and the complexity of the constraints.

3

Evaluation of the circularity constraints in the European Union’s photovoltaics supply chain

The third chapter covers the application of the tool with the proposed methods. The chapter includes an analysis of the EU’s PV CSC and the identified constraints, enablers, and goals. The results of weighting indicators and input collections from CSC are presented. Furthermore, the TOPSIS results are discussed, followed by theoretical and practical discussions. Lastly, the analysis of the theoretical framework model for the applied circular supply chain is discussed. The main research findings of this Chapter are published in the author’s publication (Radavičius et al., 2025).

3.1. Analysis of the European Union’s photovoltaics circular supply chain

As a basis for the investigation of CE constraints, the EU’s PV circular supply chain system must be determined first. The focus is only on silicon-based PV modules that comprise more than 90% of the market share.

The capability of each country to ensure renewable energy generation is one of the priorities for successfully achieving climate neutrality. The European Commission, which leads the European Solar PV Industry Alliance, set a goal to achieve 30 GW of PV products (modules, cells, ingots and wafers, polysilicon, and metallurgical grade silicon) produced in the EU by 2030 (PV Manufacturing in Europe,… n.d.). The goal is also aligned with the Net Zero Industry Act (NZIA) to achieve a sufficient PV module manufacturing capacity in the EU by 2030, which would be sufficient to install at least 40% of the total EU's PV modules market with modules made in the EU. Figure 3.1 shows 2023 data on the EU's PV industry plans to increase production. It is expected that an additional 23 GW to 8.3 GW of PV modules will be added, and the capacity for PV components production will increase.

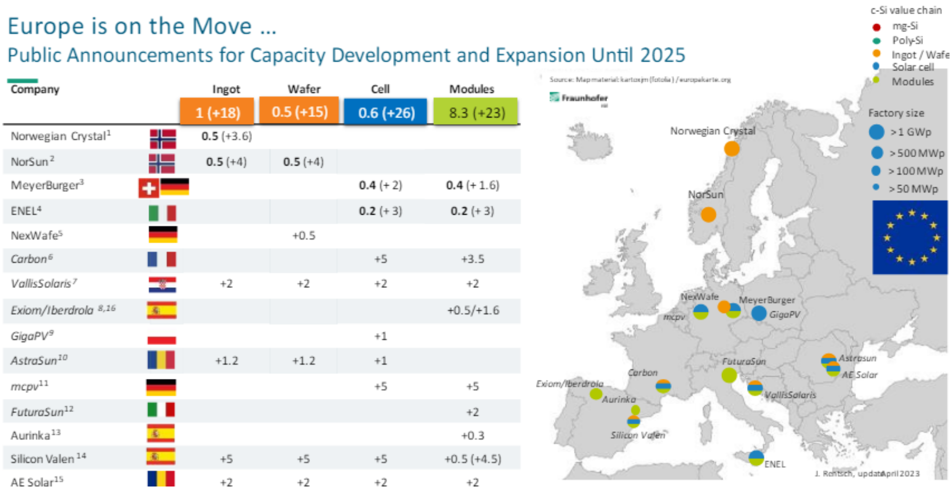

Fig. 3.1. Circular supply chain of the PV industry
(source: PV Manufacturing in Europe,… n.d.)

According to the latest data, instead of opening new factories, the EU's PV industry may have lost ~3 GW of PV module production capacity by 2024 (Newsletter Detail – Swiss Trade, n.d.; Exasun Files for Insolvency – Pv Magazine International, n.d.; Meyer Burger to Discontinue PV Manufacturing in Germany, n.d.; French PV Module Maker Systovi Goes into Liquidation – Pv Magazine International, n.d.; Recom Subsidiary Sillia Closes Plant in France and Moves to Italy – Pv Magazine International, n.d.; Solarwatt Shuts down Battery Factory in Germany – Pv Magazine International, n.d.). Within the ingot production, Norwegian Crystal also had to shut down, leaving ingot manufacturing capacity in the EU only in the hands of the NorSun company (*Insolvency of Norwegian Crystals*

Is a Blow to PV Supply in EU, n.d.). It is expected that the EU's PV industry will continue to decrease until EU actions, such as the NZIA, are implemented in each EU member state. It could take years before NZIA generates results. Something that the EU's PV industry does not have compared to China is extensive subsidies dedicated to their PV industry that floods the EU market (*With Solar Industry in Crisis, Europe in a Bind over Chinese Imports | Reuters*, n.d.). The EU must find a competitive advantage with made-in-EU PV products. Circularity can be one of them.

Generally, the PV supply chain can be split into three phases: upstream, midstream, and downstream (Frantzis et al., 2008; Garlet et al., 2020). While the PV supply chain has often been considered only from material extraction to manufacturing and installation (Zhang & Gallagher, 2016), this paper takes a more holistic approach that allows all circular strategies to be included. Consequently, the usage phase, de-installation, and end-of-life steps are considered.

The PV upstream supply chain consists of the following steps to produce solar cells: silica sand extraction, metallurgical silicon production, polysilicon production, ingot moulding, and silicon wafer production. These supply chain steps are characterised by high entry barriers and, thus, relatively low competition, which is mainly due to the high initial capital requirements and the high energy intensity combined with the need for specific technological equipment, considerable process know-how, and specialised labour (Zhang & Gallagher, 2016). Structural parts that complement the PV cell to an entire PV module encompass cables, glass frames, back sheets, encapsulation films, ribbons, and junction boxes (Garlet et al., 2020). Thereby, different tier suppliers, such as steel, aluminium, glass, and plastic producers serve as providers for those component producers. The last steps in the upstream supply chain, e.g., PV cell and module production, are characterised by highly efficient resource utilisation and comparatively low added value per supply chain step, which, therefore, have low entry barriers and, consequently, high competition. Generally, the massive concentration of production capacities in these upstream supply chains in China deserves special mention. For example, China accounts for 85.1% of cell production capacity or 96.8% of wafer production capacity, with one single wafer production facility responsible for 14% of global production capacity (IEA, 2022).

In the downstream supply chain, PV modules are completed with the balance of system (BOS) components to form a PV system. BOS components, which are produced in a side-stream supply chain, consist of a fastening structure, inverter, string box, and meter (Garlet et al., 2020). First, the PV system distribution and integration take part, where the BOS components are combined with the PV module, and then the PV system is installed. In this downstream supply chain step of PV installation, there are several ancillary services, such as project management, financing, and insurance. Next, PV system operation and maintenance follow, which is compared to the other supply chain steps in the downstream supply chain. It is not a one-shot step but rather ongoing over the whole life cycle of a PV system. It encompasses energy purchases and sales based on under- and overproduction, as well as monitoring activities as auxiliary services (Frantzis et al., 2008; Schoettl & Lehmann-Ortega, 2011). The further step is PV system deactivation and dismantling once the PV system reaches the end of its first life cycle, where BOS components are again separately treated in side-stream supply chains.

Along the downstream supply chain, PV modules are collected, tested for reuse, recycled if not applicable for a second life and finally, the material is recovered. Once PV modules are uninstalled, they are collected, sorted, transported, and stored under the Waste Electrical and Electronic Equipment (WEEE) directive (Mahmoudi et al., 2021). PV modules that are potentially suitable for reuse are then tested and, if suitable for a second lifetime, returned to the usage stage for resale and reinstallation (Tsanakas et al., 2020). The PV modules that reach the next phase are recycled, and their materials are recovered in the last two steps of the downstream supply chain. Four phases can be distinguished: (1) the structural parts are disassembled and separately recycled, and materials such as aluminium and copper are recovered, (2) the laminated structure of the PV module is opened using thermal, chemical, or mechanical processes depending on the target material, (3) the different materials are sorted, grouped, and processed in purification or extraction steps, and (4) the different material groups undergo refining treatments to obtain high-purity end materials (Deng et al., 2022). The material consumption of one standard wafer-based crystalline silicon (c-Si) module per 1 megawatt (MW) (1 MW of PV modules is ~3000 PV modules) is estimated to be 46.4 t/MW of glass, 8.6 t/MW of plastic, 7.5 t/MW of aluminium, 4.6 t/MW of copper, 4 t/MW of silicon and 0.02 t/MW of silver in a high demand scenario (Bronshtein et al., 2018; Carrara et al., 2020; Jean et al., 2015).

Figure 3.2 summarises the representation of PV CSCin. It starts with the extraction and preparation of raw materials, which are used to produce components and the final manufacturing of the PV module. Then, it is followed by usage, EoL management, and recycling.

The material consumption involves PV system mounting parts as well. The high demand for materials and usage of silver and copper challenges the sustainable usage of PV technology. Considering that it is expected that in the year 2030, 4 terawatts (TW) of total worldwide capacity (1 TW = 1 000 000 MW), the material consumption will be massive in the PV industry worldwide. The downstream supply chain consists of PV deployment (installation, PV project development), reuse, and recycling. The challenges of circularity improvement for the EU's solar PV industry are:

- Production of components that are required to generate RE is concentrated outside the EU.

- High material consumption, especially for silver and copper.
- Underdeveloped EoL processes.

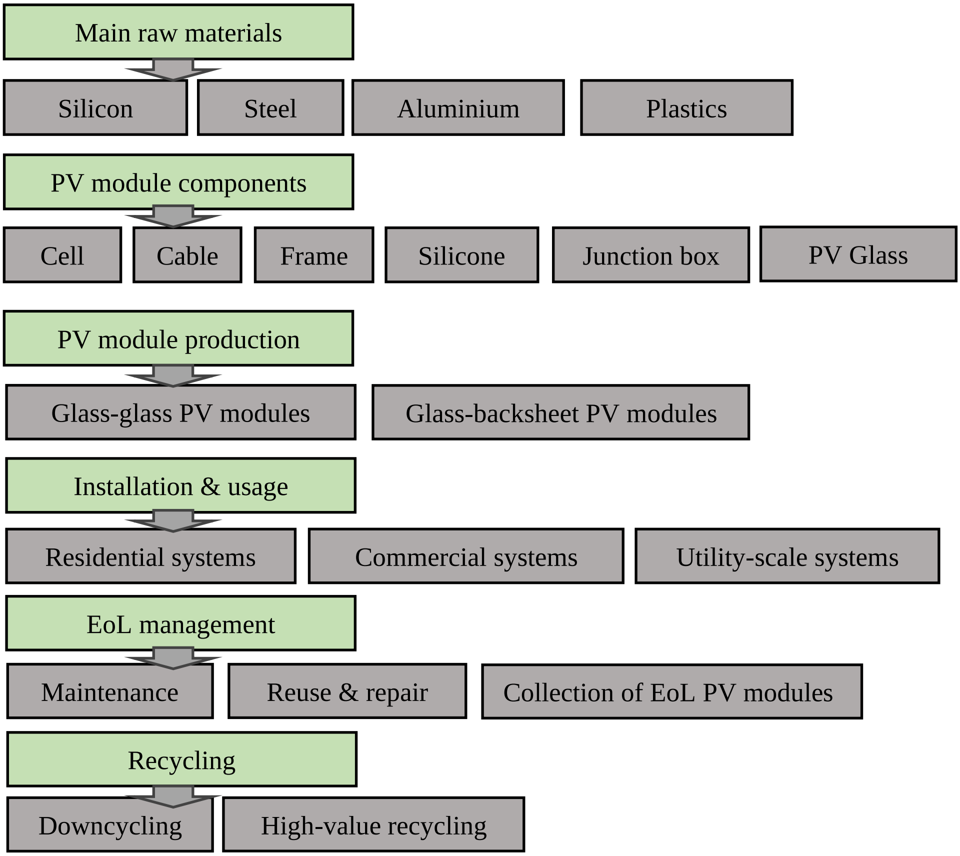

Fig. 3.2. Circular supply chain of PV industry (source: composed by the author)

Various strategies are available to address the challenges. Reusing old PV modules in new systems allows the extension of PV modules' lifetime at the cost of reduced efficiency. Repairing PV modules improves their longevity. Recycling offers material extraction from old PV modules. However, currently, most of the PV modules are exported for reuse. There are no standards to classify whether the solar module is safe or economically viable for reuse (Deutsche Umwelthilfe, 2021). Unclear legislation, difficulties in sourcing potential modules for reuse from small PV systems, and other challenges hinder the reusability potential (IMEC, 2021). The dominant mechanical recycling approach, which lowers the quality of recycled materials, and the lack of standards for repairing, further hinders circularity (Tsanakas et al., 2020). Other CE strategies, such as reduction of materials usage or design for circularity, could improve the circularity of the EU's PV industry.

Considering the proposed CE indicators for measuring circularity in circular supply chains, the current situation in the EU's PV CSC can be analysed. At the moment, there is no reuse content in PV modules as it is difficult to reuse glass, aluminium frames or junction boxes from old PV modules. Due to the fast technological progress of the PV industry, older components do not meet the current requirements for quality, dimension, efficiency, etc. What is reused is the whole PV module, which still has around 85% or more efficiency after 20–30 years. Recycled content, up to 30%, is present in PV glass if it is made in the EU. The EU regulations demand glass producers to use 30% of recycled glass. No renewable content is present in PV modules. Some prototypes contain PV module frames made from wood, but due to PV module longevity, all components need to be lasting; thus, renewable content is not present in PV modules. The lifetime of glass-backsheet PV modules is around 25 years, with glass–glass having 30 or more years. EoL PV module glass, if cut cleanly, can be reused in other industries. Other components are not yet reused. The recycling rate of a PV module is around 95%, but in terms of materials quality and extraction of rare metals, such as silver, there is a long way to go. Only metallurgical grade silicon is recycled at the moment, while silver and other materials are lost. The plastics are usually burnt or disposed of. Most recycling facilities, that are not dedicated to recycling PV modules, recover only aluminium, cables, and glass, with the rest of the materials going to landfills. None of the materials or components can be recirculated back into the biological cycle as some of those materials are not biodegradable.

The PV supply chain and its relevance for circularity improvement demonstrate the need for analysis and potential improvement of circularity processes in the EU's PV industry. The PV industry has complex products in terms of technical characteristics, multiple layers in the products and components, etc., and with supply chains across multiple countries, mainly outside the EU, it is a challenge for CE solutions.

3.2. Results of circular economy constraints, enablers and goals of the European Union's photovoltaics circular supply chain

The following sub-chapter discuss the results of content coding from interviewee transcripts from 20 EU's photovoltaic circular supply chain organisations. Each sub-chapter discusses the following results: constraints, enablers, goals, and results comparison to other researchers.

3.2.1. Circular economy constraints of the European Union's photovoltaics circular supply chain

MAXQDA was used to code relevant sentences related to CE constraints, and the result was 20 code categories and a total of 106 codes. For a specific code category, no more than one code was taken from each interview. Table 3.1 shows the list of CE constraint code categories, the number of codes, and the number of circular supply chain stages in the category.

Table 3.1. List of identified constraints in EU PV industry CSC (source: made by the author)

CE Constraints categories	Total number of codes	Amount of different CSC stages participation (1 to 6)
1. Unpredictable volumes for reuse and recycling	11	5
2. Insufficient value chain collaboration	8	5
3. Insufficient purity of recyclates for reinsertion in PV production	7	3
4. Uncoordinated legislation over Europe	7	4
5. Hesitant exchange of information	6	3
6. Insufficient traceability of PV modules	6	3
7. Immature recycling methods, often resulting in downcycling	6	3
8. Illegal PV module exports	6	3
9. Underdeveloped reverse supply chain	6	3
10. Conventional PV recycling not profitable yet	6	4
11. Changing materials inserted in PV production over time	5	4
12. Low-risk appetite for investments in industrial-scale recycling	5	2
13. Underdeveloped regulatory frameworks	4	3
14. Cheap virgin raw materials	4	2
15. Missing PV module design for circularity	4	2
16. Poor viability of circular business models	4	2
17. Strong competition from non-European countries	3	3

End of Table 3.1

CE Constraints categories	Total number of codes	Amount of different CSC stages participation (1 to 6)
18. Difficult access to external byproducts	3	2
19. Underdeveloped secondary material markets	3	2
20. Fluctuating supply of byproducts	1	1

The most mentioned identified CE constraints are:

1. Unpredictable volumes for reuse and recycling;
2. Insufficient value chain collaboration;
3. Insufficient purity of recyclates for reinsertion in PV production;
4. Uncoordinated legislation over Europe;
5. Hesitant exchange of information;
6. Insufficient traceability of PV modules;
7. Immature recycling methods, often resulting in downcycling;
8. Illegal PV module exports;
9. Underdeveloped reverse supply chain;
10. Conventional PV recycling is not profitable yet.

Further, the research goal is to conduct structured interviews with EU PV organisations about how identified CE constraints affect indicators. It is necessary to ensure sufficient time for interviews. Assuming one hour as a limit during interviews, the maximum amount of constraints that could be discussed is ten, as with nine indicators, a total of 90 inputs are required. If more input is required, likely, a 1-hour interview would not be sufficient. Thus, further in-depth analysis of only the top ten identified constraints will be discussed and used in further research.

Unpredictable volumes for reuse and recycling

The most noticeable constraint for the EU's photovoltaic circular supply chain is the unpredictable volumes for reuse and recycling. Eleven out of 20 interviewed organisations face the constraint. The constraint was reported by five out of six CSC stages. The first stage of PV CSC interviewee (from organisation G) stated that "*...waste stream will of course increase exponentially as older modules are changed out fading. But we won't see the crazy numbers on let's say 5–10 years, but it will come, and it will come fast...*". Materials producers are aware that PV modules' lifetime is very long, around 30 years. Thus, their waste in large numbers will only be present later. Components producers also notice a value in the waste of PV modules, interviewee D (CSC stage 2) stated, "*at the moment, there just isn't enough modules being collected*". Additionally, interviewee B (CSC stage 2) suggested that "*it will be very important how to deal with these big volumes of modules*". Both component producers see the potential of using EoL solar modules, but it is not yet clear in terms of volumes when recycling will kick off, so component producers and material producers could use some of those recycled materials. Product manufacturer representative (organisation I, CSC stage 3) pointed out the issue in PV module recycling, stating that "*...you have 5000 to 10 000 tons of modules per year*". A PV module recycler (organisation U, CSC stage 6) confirmed that "*...(PV recycling) needs large volumes...*". Another interviewee (recycling company) stated, "*Unfortunately, I can't operate (2 000 tons of PV waste) with that for more than a year*". With unknown waste streams, it is difficult for recyclers to conduct their business.

An interviewee from PV module waste collector (organisation P, CSC stage 5) highlighted one of the main issues "*...at the moment, 1% of PV modules sold are disposed of*". The issue lies in the longevity of PV modules, which means the waste stream will happen only in the future. But that is not all; the same interviewee additionally mentioned that "*...not even one park (PV system park) is disposed of per year because they all either go abroad or are disposed of illegally*". Another interviewee also suspected of high illegal PV waste treatment (organisation O, CSC stage 5) "*it was predicted that in 2020, Germany will have 100 000 tons of solar module waste. However, scarcely 7000 tons are reported*". PV waste is now exported abroad or handled illegally, whereas EU PV recyclers cannot get sufficient amounts of PV waste. An interviewee from an organisation that reuses PV modules (organisation N, CSC stage 5) confirmed the previous organisation's statement on illegal PV treatment "*...then also there are those who steal the product from the recycler, so to speak*". When PV waste occurs scarcely across the EU, it is managed inappropriately, as interviewees suggest.

The lack of prediction of PV waste volumes for reuse and recycling hinders circularity in the EU. The current situation is that organisations are handling PV waste illegally or not ensuring that it can be reused or at least properly recycled. Without understanding the volumes, recyclers are not able to start their business as a sufficient and stable amount of PV waste is required.

Insufficient value chain collaboration

The lack of supply chain collaboration is visible in the five stages of the CSC. Interviewee R (CSC stage 6) suggested that "companies don't work together. You see, you have upstream, they have the production cells, downstream (has) end users. Everybody has a different target (in) his or her life. So, a harmonised goal is missing completely". Agreement on solving specific issues is lacking. Interviewee L (CSC stage 5) implied that there is a huge gap in the understanding of the EoL management and recycling in the upstream supply chain: "*the solar industry has no clue how recycling and waste business work and how people make* *their money and how it comes that even if there is a little bit of seven milligrams of silver in the solar panel that we do not receive today money for that solar panel*". The lack of understanding about the challenges organisations face limits the CSC cooperation opportunities. The waste of one organisation within or outside the CSC can be a source of secondary materials for another organisation. Interviewee G (CSC stage 1) describes the mentioned issue in the following way: "*it's always difficult when you are starting to take a byproduct from somebody's process and make it your main raw material. ...there's always a big challenge there because they're used to handling this as a low-value byproduct. But we have to standardise their process on how to take it out. It's not a lot we need to do, but we need to make the customer aware of the fact that this is more valuable than they think*". While recycling is already happening, although mostly downcycling (loss of quality of the materials), another issue is the demand for those materials. Interviewee J (CSC stage 4) suggested that "*...so we have to have a market that addresses the value of those components (of the solar module) and make them reusable or take that value out and minimise the waste placed. So that we can reuse them as a source for the PV industry but also minimise the waste*". The issue is related to a lack of cooperation between the organisations within the supply chain. Interviewee B (CSC stage 2) supports the issue as "*They do not come. They (PV module producers) never contacted us (component producer) asking what can we do with the part of the (component). I do not know how they handle their recycling. They don't ask us there ... it's not a discussion, not once in a year*". The lack of cooperation within the supply chain is a hurdle for multiple organisations within the CSC.

With the currently small amount of recycling, there is no motivation for the EU's CSC to communicate and find solutions. Organisations at each CSC stage have their goals, and there is no alignment made in terms of CE for specific targets to achieve as a whole industry. Considering that PV waste will be exponential in the next decade, it is a risky endeavour to wait for those volumes to appear and then work as an industry to solve it. One of the risks is that illegal exports of PV module waste can grow and prohibit the expansion of PV waste recycling. Another risk is that upstream CSC will keep sending PV modules to the market without considering what they could do to improve repairability, recyclability, etc. Thus, the lack of collaboration can damage the industry's CE.

Insufficient purity of recyclates for reinsertion in the PV production

After recycling, materials fall below their quality requirements for reinsertion back into the upstream PV supply chain. Interviewee A (CSC stage 2) faced this issue: "*So we can't go anywhere, and the main limitation at the moment is the price. And on the other hand, the quality of the available (material) or the availability of the (material) in the quality that we need, right quality*". The reduced quality of the materials is not sufficient for the upstream PV industry, but it can be used for other industries. Interviewee S (CSC stage 6) suggested the following: "*Yes, the purity is still low. They do not go back to PV but for other applications. And that's not an issue at all. Well, so you don't necessarily have to close the circles, but it's enough to find another use*". Another PV recycler, interviewee R (CSC stage 6), stated, "*The problem of PV modules is related to the waste stream, there is antimony, it's not allowed for production of new flat glass*". Specific materials in PV waste prohibit recyclers from reintroducing them back in the materials flows. Components producer's representative E (CSC stage 2) mentioned that "*...after quality inspection (of recycled materials), we see that they are not suitable for PV for reusing in PV cell production*". The quality requirements are well above what the recycling industry can offer. The highest quality must be reached for different components of PV waste as interviewee M (CSC stage 6) suggested "*...to bring highest quality as possible for all the different components to get high-quality silicon, to separate silver, to get high-quality glass that can be reused in the flat glass industry*". The recycling organisation's representative pointed out a difficulty in glass recycling "*I think the main challenges are the glass. Requirements of glass manufacturers are really high and also high for silicon and silver*". Interviewee D (CSC stage 2) highlighted another issue: "*But if you are going to get material to last for more than 25 years, it's got to be same as virgin material (after recycling)*". The PV industry improves materials quality every year, and when that material attempts to re-enter material flow after 25 or more years, it becomes difficult to ensure that it meets today's quality standards for materials.

While the quality requirements for the PV industry are strict, the issue of the recyclates' quality is of high importance if the EU's PV CSC wants to improve performance in CE. Achieving high-quality recycled materials requires the collaboration of the whole CSC. In addition to that legislation, other forces should pressure or motivate the industry to work on CE issues.

Uncoordinated legislation over Europe

Each EU member state has its regulations on how to handle waste, including that from PV modules. The common issue is that there is no clear responsibility translated as who is responsible for the recycling of PV modules, as interviewee M (CSC stage 6) suggested, "*But the PV system operators do not know that they are responsible for recycling*". Besides the unclarity of who is responsible for what, different PV modules are available on the market. The regulatory perspective offers insufficient clarity on how to process specific modules. Interviewee F (CSC stage 2) described the issue in the following way: "*So how easy is it to recycle, how the modules (perovskite modules) be classified in the waste stream if they are not applicable for using the current standard (of recycling), what will be the clas-*

sification?" Tens of thousands of different PV modules are available on the market, and without proper sorting, it is difficult to implement high-value recycling. Another lack of clarity in terms of legislation is how to compare the life cycle assessment of different PV modules. Interviewee I (CSC stage 3) states that "*there is only one (low carbon third-party LCA assessment standard) test used in the French market, they calculate the footprint without the aluminium*". Another interviewee (organisation R, CSC stage 6) spotted the same issue "*...we need a common language in terms of LCA. So we have a baseline, and we know that we are comparing*". It is difficult for the downstream supply chain to purchase low CO_2 PV modules with a lack of LCA standards to compare them.

Issues occur as each EU state handles waste collection in their way. Interviewee L (CSC stage 5) pointed out, "*it's only in France and Belgium that we are present with accreditation or at least with approval by the government. Let's put it like this: in Flanders, it is a license; in Belgium, it's more of an approval written down in cooperation between government and industry. In other countries, the Netherlands, we are pushed away from the market because the government decided to only have one thick system in place for all electronic equipment*". Some countries have general organisations that collect various waste, which limits the potential to improve sorting. Other countries have only one waste collector organisation, which gives no motivation for the organisation to improve EoL management, especially since those organisations that collect waste cannot be profit-based companies. Another waste collector representative (organisation P, CSC 5) stated the following: "*...manufacturers are only complying with the legal requirements for the laws. For a manufacturer, of course, it's not so nice to have a used car market for your product because they (manufacturers) say anyone who might have a used module is a potential not buyer of a new module*". There is a lack of pressure or motivation for organisations to ensure the reusability of PV modules. When the components producer's representative (organisation B, CSC stage 2) was asked whether they felt regulatory pressure to increase sustainability in their company, the interviewee answered, "*We don't, we do not feel or see any pressure to be honest*". There is a lack of incentives for the EU's PV CSC to improve circularity with current regulations.

Uncoordinated legislation in the EU hampers circularity. With the current lack of PV waste accumulation in the whole EU, the recyclers cannot start their activities. It might not happen soon when sufficient waste arrives at recyclers as the waste is exported abroad or managed illegally. Higher clarity and coordination of EU states on regulation are required; otherwise, mishandling of PV waste for recycling or reuse will not disappear on its own.

Hesitant exchange of information

Information sharing and access to it are an important part of establishing CSC. Interviewee J (CSC stage 2) pointed out that “*there is very little available data like environmental product declarations of LCA. Currently, that is a challenge to be more transparent*”. There is a lack of motivation to share information with some CSC organisations. Interviewee E (CSC stage 2) implied that “*Not always we can get all information which we need. A lot of information is already available in the material data sheets, they are forced to issue it*”. Organisations are forced to share some specific information, but not all of the information that would positively impact CE processes in CSC. Interviewee G (CSC stage 1), which uses the production waste of other organisations in the EU’s PV CSC as a source of secondary materials, is facing the following issue: “*IP intelligent is influencing this (information sharing) because if they (suppliers of production waste) tell us what kind of supporting plate they use (they need to know it to understand quality of production waste), they might be thinking that we give this information to their competitors*”. There is no motivation to disclose information that could improve circularity. Interviewee F (CSC stage 2) suggested that “*The reason (for not sharing information within CSC) is because the components to the very end of details is your IP*”,”*…I don’t think disclosing everything is a good approach to take because many manufacturers are already against and I understand why, we are fully supportive of any initiatives that are heading towards a better management of any assistance, but that is the level of disclosure has to be managed carefully*”. Recyclers would benefit from full product disclosure on what products are made of, but the manufacturers are careful of such an approach. Interviewee L (CSC stage 5) attempted to collect relevant data for CE: “*We did it in first years. Collecting data on brands, how old modules are, where they come from, the origin of failure*”. But because there was no regulatory pressure for it, they ceased to collect such information. It is difficult to use CE-related information to improve circularity when the data is of poor quality or if data is lacking.

Hesitant change of information within EU PV CSC is one of the CE constraints. For proper EoL management, improve the design of products for circularity, etc., data is essential. When there is no motivation or pressure to exchange information, organisations do not commit to it.

Insufficient traceability of photovoltaic modules

The exchange of information is lacking within the EU’s PV CSC. One of the specific applications for information sharing is to implement traceability of PV modules. A representative E of a PV module components organisation (CSC 2) stated that “*data which could come from the recycler or the user of our materials could help, of course, to make design changes*”. Interviewee (CSC 5) suggested that “*we need to know where we have to pick (PV modules), where we collect them. So this* *tracking and tracing, this information we need to have*". While the benefits of traceability are clear, manufacturers are not obliged to implement traceability solutions. Recyclers need a standard that most PV modules would follow in terms of traceability. Currently, the process to assess what PV modules are on the field is, as interviewee O said, "*documents from installation or you take a quick picture of the nameplate*". The nameplate or installation documents do not specify what materials are inside the module. Considering the PV module's longevity, it is very likely that even if you know the original manufacturer, the company might cease to exist as 20 or 30 years can pass before the PV module needs to be handled for EoL. Interviewee M (CSC stage 6) points out that "*currently, it seems to be hard to get access to this (product composition) information because I'm not even sure that the PV module manufacturers know exactly the silver content in the module or silver paste composition*". The issue of traceability starts at the beginning of CSC and starts with the materials suppliers. If the component or product manufacturers do not know the composition, then there is no hope that recyclers will know it.

To implement traceability of information on PV modules, all CSC organisations need to participate. It is unlikely that organisations will create their standards on how to do it as the costs to implement it usually will be at upstream CSC, while the benefits will reap downstream CSC. Thus, upstream CSC has little to no motivation to do it.

Immature recycling methods often result in downcycling

The downcycling recycling approach results in lower-quality recycled materials. The low quality of materials leads to difficulties in reinserting them back as secondary materials to their original supply chains or in other industries. Interviewee L (CSC stage 5) suggested that "*a recycler tries to maximise the value of the materials. And he (recycler) also knows that he will have cost with some materials he has recovered. So, at the end of the day, he makes sure that, yeah, net balance, he has still somewhere to profit. And if he's still able to give something back to us because we deliver him for a year, I don't know, 50,000 tonnes, then we might have a chance that he will give us a bit of money back and this will maybe then lower the cost of the recycling fee*". Recyclers are aiming to maximise profit, as interviewee P (CSC stage 5) suggested "*there are also disposers, for example the scrap metal dealers, who have a very high demand for scrap metal, who simply take these PV modules and forcibly remove the aluminium frames to make this aluminium money. They don't care about the module, they don't care about the silicon, they don't care about the glass. They just want to have the precious aluminium frame*". The recyclers' goal of maximising profit leads to the issues of other CSC parts, where their goal is to receive secondary materials at a specific level of quality. For recyclers, it is difficult to process PV modules as interviewee

D (CSC stage 2) stated, "*...solar module is like a sandwich that has layer by layer structure which is glued very strongly*". The sandwich-like structure of the PV module is not something that can be recycled with simple processes. Interviewee S (CSC stage 6) highlighted one of the issues related to poor recycling processes: "*Just take silicon modules, glass is recycled, aluminium cables too. Then, it is sorted immediately. Nobody knows what happens to the rest (the rest of the materials). With 5000 tons of PV modules recycled, 50 tons of plastic, silicon and silver is thrown away (with current recycling methods)*". Even though the glass is recovered, it is difficult to reintroduce it, as interviewee Q stated (CSC stage 6), "*Unfortunately, we are not yet able to put it back (recycled PV module materials) into high-grade or higher-grade applications, such as flat glass*". The lack of recycling processes limits materials flow back into the same or other industries.

On one hand, it is recyclers who should be responsible for the product's recyclability; they can only do what is possible in their hands. Without knowing what is inside the PV module or additional sorting done by collectors, they are limited in their actions. Especially if considering the lack of waste for recycling as it is currently managed inappropriately (shipped abroad or managed illegally).

Illegal end-of-life photovoltaic module exports

Illegal EoL PV module exports were mentioned in previous constraints as a reappearing hurdle for CE. The illegal exports of EoL PV modules block the potential for PV modules' reuse and recycling activities. The significance of the issue was described by interviewee P (CSC stage 5): "*I would say from the gut that at the moment we have the problem that 90% of all old PV modules go abroad. And of that, probably another 90% by not quite legal means*". The exports of EoL PV modules outside the EU pose the risk of losing materials and dumping the waste in another continent. Interviewee N (CSC stage 5) described the risk in the following manner: *"So, the whole topic of talking (PV module exports), we have to look closely at what we do, that (in) Africa like other electronics things becomes a dump. So, we need just rules, especially for big energy suppliers. There, I also wanted to try and look at their policy, which can be asked for available chains. And around it goes on the serial number at the basis tracking. Which one? Where in Africa? With whom does the module end up, and with which serial number? There are different interests. But there, we have to find rules between Europe and the real needs in Africa".* Additionally, the interviewee stated, "*In Germany and Europe, there are now a lot of colleagues of Arab origin who run across the market and buy containers filled with modules (EoL PV modules)*". The illegal exports of EoL PV modules outside the country and the EU decreased the potential of using EoL PV modules for reuse applications inside the EU and in recycling facilities to generate secondary materials.

Other organisations also mentioned the issue of shipping EoL PV modules to Africa or Asia. There is a high leakage of materials, such as aluminium, silver, and glass. With increasing illegal shipments of EoL PV modules, recyclers in the EU will not be able to get sufficient amounts of waste for their operations. Furthermore, without launching recycling equipment, there will be more delays in understanding what issues PV modules contain and finding solutions to improve recyclability.

Underdeveloped reverse supply chain

A reverse supply chain refers to the processes of managing end-of-life materials, components, and products for circularity purposes, whether it is to repair or recycle a product. PV CSC lacks attention to the reverse supply chain, as one interviewee T (CSC stage 6) mentioned: "*When some company wants to dismantle a PV system, they ask us if we can utilise it if we have enough capacity; we visit these panels to check if its good (whether it is not deformed). Because our machines, of course, are mechanical, that means we need to have a flat module without deformation*". It is important to properly manage EoL PV modules to improve recyclability. Another issue that recyclers face was mentioned by interviewee M (CSC stage 6): "*The way the modules are packed on the pallets must not bring any breakage during the transportation. We saw in France that 15–20% of the modules that we stored on our site were broken*". The inappropriate handling of EoL PV modules also hinders reusability of PV modules, as said by interviewee O (CSC stage 5), "*It is often the case that everything, that is 99% of all modules that come through the recycling yards, unfortunately, been treated so badly*". It is less likely for PV module to be reused if it is damaged. It is also important to know what is inside the PV module, as interviewee P (CSC stage 5) stated, "*Can you run your fingernail over the back foil and see if it has phosphorous? I can't ask for something like that. That is only found out in the disposal plant*". Organisations that inspect PV modules for reusability have little information on what is inside the PV module.

Limited progress can be made in CE if the products are not sorted, handled and managed carefully. Identification of these constraints is required to know the hurdles so that they can be addressed by policy, standards or other means.

Conventional photovoltaic recycling is not profitable yet

One approach to CE in CSCs is to leave it in business hands if there is profit from making circular actions. In the EU's PV CSC case, it is yet not profitable to recycle PV modules, as interviewee C (CSC stage 2) stated, "*If we take recycled material and put it in our materials, for the moment, I think the cost difference would be like 20%*". Recyclers are required to improve scalability and processes to decrease costs per recycled material. Another interviewee (D, CSC stage 2) mentioned that "*It's not the focus of the PV recycling industry (the plastics in the PV module). So that's a financial problem or just a scarcity of resources problem for the growth of the industry*". Plastics value is too low for recyclers to make money. Thus, they choose not to invest resources in properly recycling plastics within PV modules. With unclear regulations of who and how should pay for recycling, there are gate fees at the recycling organisations, as interviewee L (CSC stage 5) said, "*When you enter the recycling or waste treatment plants, you have a fee to pay today in most of the cases*". Recyclers face issues with dopants in PV modules. Dopants (usually Phosphorus or Boron) are present by weight only below ~0.0001%. Nevertheless, as interviewee R (CSC stage 6) stated, "*...we don't go beyond metallurgical grade silicon recycling quality mainly because of the doping (in the silicon by manufacturers) because of the cost issue (in purifying/removing dopants)*". Even an incredibly small amount of materials that are present in PV modules hinders recyclability.

Other organisations stated that it costs around EUR 120 per ton of PV waste to recycle PV modules. Additionally, they mention that very little is paid upfront when selling PV modules for recycling in the future. To ensure proper PV module recycling, the recyclers need to have a business case for it. If not, there should be policy instruments to support recyclers, increase the price for recycling when a new PV module enters the market, and improve recycling technologies or other solutions.

Mostly mentioned CE constraints within the EU's PV CSC were discussed. Each of them is interconnected, especially the illegal management of EoL PV waste in the EU. The rest of the constraints will be discussed further.

Changing materials inserted in photovoltaic production over time

The EoL management benefits from knowing the material composition of a solar module. The reality is that it is difficult to ensure the traceability of materials' contents when they are always changing. One organisation mentioned that it might be no issue to recycle or use a component if its lifetime is around ten years, assuming it is clean and not damaged. And if it is older, it is a question of whether the recycled materials can be used without the need for additional purification. Different plastics in a PV module that glue the PV module components are very different. Recyclers mention it as one of the issues: if they do not know what plastic it is, they cannot attempt to recycle PV modules properly. For other recyclers that use pyrolysis-based recycling (in very high temperatures, adhesion is destroyed), it does not matter what materials are inside. However, for high-value recycling, it is always beneficial to know what is inside the product.

Low risk appetite for investments in industrial-scale recycling

The meaning of this constraint is that investors are not looking to pour their resources into PV module recycling. Interviewed organisations stated one reason: the EU's PV industry had a crisis a decade ago, and the result was that the industry moved to Asia (PV manufacturers). Small recyclers with innovative recycling processes face issues related to the required high investment in personnel and the overall management of the recycling plant. Even receiving a licence for building a recycling plant can take a couple of years with lots of time investment in preparing documents.

Underdeveloped regulatory frameworks

Interviewed organisations mentioned issues in Waste Electrical and Electronic Equipment (WEEE) directives and similar frameworks that address circularity regarding PV modules. One of the issues is that the directives' goal for PV modules is 80% recyclability. As two of the recyclers stated, the PV module in itself contains more than 80% glass, which is easily recyclable with any shredding machine. The problem lies in focusing on the precious materials, such as silver or high-purity silicon.

Cheap virgin raw materials

Component producers suggest that there is no incentive for recycling PV modules when virgin raw materials, such as very cheap silicon, can be produced easily from abundant silica in the world. Additionally, the logistical costs of EoL waste treatment make secondary material more expensive than virgin raw material.

Missing photovoltaic module design for circularity

The sandwich structure of the PV module is not something that can be dismantled easily. The recycler mentioned that the back sheet at the back of the PV module contains different types of polymers. It is a problem, as each PV module's back sheet composition is different. There is a lack of design to standardise or simplify the PV module's structure for easier recycling. A components producer pointed out that if a product is designed to last 25 or more years, it cannot be expected to be recycled using simple means, such as mechanical recycling. A materials producer engaged in the production of a component of a PV module stated that they have no point in making any design for circularity as their material will be used for a component, which will be further assembled with other components to a final product, a PV module. Changes introduced by a materials producer would have no meaning if other organisations did not make any changes.

Poor viability of circular business models

Circular business models aim to deliver value to customers with circularity incorporated, such as ensuring proper collection, repair, longevity, reusability, etc. The organisation mentioned that it is difficult to start the reuse of EoL PV modules when a warranty cannot be provided and there are no methods to assess the remaining longevity of the PV modules. Component producers have no motivation to make their components reusable or easily recyclable. They do not get feedback from PV producers on what they could improve as they have little to no warranty claims coming to them. A claim is when a customer contacts a product manufacturer due to a defect in the product. Additionally, these claims do not reach component producers; thus, no feedback is received. And since some components' economic value is low, they state that there is no motivation to make the components or materials reusable or recyclable.

Strong competition from non-European countries

Material producers mentioned that due to high competition from China, it is difficult to reintroduce secondary materials back into the PV industry. The high difference in material prices due to the usage of secondary materials compared with virgin raw materials is not an attractive offer for PV component producers. EoL management usually involves higher labour costs compared to manufacturing. In this case, the organisation indicated that with EU labour costs, it is difficult to ensure circularity at the EoL stage.

Difficult access to external byproducts

The byproducts mean production waste of other organisations. Materials and components producers of the EU's PV CSC can process some of the waste in their operations. The issue lies in the lack of it, and in some cases, the production waste owners conduct auctions. The auctions mean that the waste will go to the highest bidder. Such an approach is not possible for materials or component producers as they require a stable supply of waste if they want to process it and sell it to clients not in batches but in stable quantities.

Underdeveloped secondary materials markets

Materials producers mentioned that they can use other producers' waste as a secondary material source. The problem is that there is no appropriate management on handling that waste as the materials producers do not know specifics about the waste. Characterisation of waste is required; otherwise, materials producers might end up manufacturing low-quality products. Component manufacturers are open to using secondary materials; the issue is with the lack of testing of recycled materials, as, for example, 20-year-old PV glass will have very different glass content compared to modern glass cullets. Thus, glass manufacturers do not take such risks. Consequently, there is a need to test and standardise secondary materials.

Fluctuating supply of byproducts

One organisation stated that they cannot forecast volumes of byproducts (waste of other manufacturers). Thus, they are not able to have a business case out of it.

Each constraint possesses a limitation for the EU's PV CSC to improve circularity. The most mentioned constraints are unpredictable volumes for reuse and recycling and insufficient value chain collaboration. Illegal handling of EoL PV waste is interconnected with multiple constraints, meaning that if it is solved, the benefits would be felt by multiple organisations. The constraints felt by multiple organisations must be lifted using cooperation. This is especially important for regulatory-based constraints, as it is unlikely that organisations could succeed in voicing the issue single-handedly without the participation of the rest of the industry. In other cases, such as the hesitant exchange of information, it is obvious that downstream CSC would benefit from higher amounts of CE-related information. But on the other hand, upstream CSC is not motivated to do so as they are not the ones who will benefit from it. Thus, an industry or policy approach is required to lift these constraints.

3.2.2. Overview of the circular economy enablers of the European Union's photovoltaics circular supply chain

The results of using MAXQDA to code relevant sentences related to CE enablers resulted in 29 code categories and a total of 137 codes. No more than one code was taken from each interview for a specific code category. Table 3.2 shows the list of code categories for CE constraints, the number of codes, and the number of circular supply chain stages in the category.

Table 3.2. List of CE enablers in the EU PV industry's CSC (source: made by the author)

List of CE enablers	**Total number of codes**	**Amount of different CSC stages participation (1 to 6)**
1. Implement internal and third-party certifications/standardisation	12	6
2. Scale up industrial recycling	10	3
3. Increase access to product information	10	5
4. Collect data to assess sustainability metrics (LCA/EPD)	9	5

End of Table 3.2

List of CE enablers	**Total number of codes**	**Amount of different CSC stages participa-tion (1 to 6)**
5. Use sustainable positioning as a unique selling proposition	7	4
6. Exploit rising market interest in sustainable products	6	2
7. Engage in PV panel design for circularity	6	3
8. Increase collaboration with recyclers	6	3
9. Engage in pilot projects	6	4
10. Engage in collaboration with plant owner/collection schemes	6	2
11. Engage in EU PV industry standards and regulations	6	4
12. Recover solar materials in high quality	5	3
13. Establish the EU's reuse market	5	3
14. Increase traceability	5	3
15. Share information with customers to prove sustainable products	4	2
16. Exploit the potential of reuse as a profitable business model	3	2
17. Build up testing and repurposing infrastructure for PVs	3	2
18. Use product identifier	3	2
19. Reinsert internal production waste	3	2
20. Collaborate with academia to test and prove recyclates	3	2
21. Create economic value	3	2
22. Sell recycling technology/as a service	2	1
23. Assign EoL responsibility to producers	2	2
24. Monitor PV performance during usage	2	1
25. Establish benchmarking among European PV producers	2	2
26. Intensify quality control measures	2	2
27. Reinsert external production waste	2	2
28. Reduce virgin raw material consumption	2	1
29. Engage in lobbying activities	2	2

The most mentioned enablers are (1) implementing internal and third-party certifications/standardisations, (2) scaling up industrial recycling, (3) increasing access to product information, (4) collecting data to assess sustainability metrics (LCA/EPD), (5) using sustainable positioning as a unique selling proposition. Representatives of CSC stages 3 to 6 are present in these code categories.

Implement internal and third-party certifications/standardisation

The need for standardisation or third-party certification means that circular processes, whether it would be selling secondary materials, production waste, or comparing product circularity, are the most relevant enablers for the EU's PV CSC. 12 organisations think that the industry needs it. Additionally, this enabler is suggested by all CSC stages.

Some organisations face issues in retrieving data related to LCA. Interviewee C (CSC 2) stated, "*When the material comes to our company, we study the emissions*"… "*another part (EoL phase) is not in our hand (the data), but at least we can provide information from the beginning to our gate*…". When calculating LCA, some data is difficult to obtain, such as emissions during the EoL management or recycling. Other companies, such as interviewee I (CSC 3), mentioned, "*CO_2 analyses and all the things, we have that calculated by institutes; they can do it better than we can*". With additional costs, LCA could be done by other organisations. Some information on emissions during recycling is generated by the recycler, as done by interviewee R (CSC stage 6), "*We do lifecycle assessment for the recycling processes, from reception to the waste disposal*…". Another missing part in the EU's PV CSC is how to assess PV systems if modules would be suitable for second-hand applications. Interviewee O (CSC 5) stated, "*we do on-site or with the laboratory first assessment*"… "*…or just from certified PV assessors make an assessment of the PV park and fly with the drone*". There are multiple ways to assess PV modules with little effort in standardising them.

One way to improve circularity is to provide a standardised and simplified way to collect LCA data. With easier procedures, LCA data could be easily accessed by the purchasers. This would allow them to compare products and make decisions by incorporating circularity factors.

Scale up industrial recycling

Higher rates of recycling could allow for increased flow of secondary materials. Even if, at the beginning, those secondary materials would be of lesser quality than their original form, feedback flow from recyclers to the rest of the CSC would increase significantly. That feedback would allow the rest of the CSC to change their processes related to the design of MCPs, collection and sorting, etc. Interviewee C (CSC 2) mentioned, "*...we have found difficulties in finding a recycling* *company knowing how to do it (how to recycle their component). The main obstacle that we have at the moment is lack of (recycling) technology*". The organisation is not able to find a recycler that could recycle their component to get feedback on what potential design issues are for recyclability. Interviewee D (CSC 2) stated, "*we have proved the principle of closed loop component to component recycling on a smaller scale, and what we want to do over the next few years is do that on a larger scale, which still won't be you know, industrial or commercially available*". With different recycling approaches being tested at laboratories, it is yet difficult to test them at industrial recycling facilities to understand in-depth feedback on recyclability issues.

Higher recycling volumes by dedicated PV recyclers would generate a learning curve in the long term. One of the organisations that recycles PV modules mentioned the issue where they didn't anticipate that PV modules would keep increasing in size. This led to their recycling machinery being incompatible with larger PV modules. Various CE issues could be spotted and solved if the feedback across the CSC were shared by the organisations.

Increase access to product information

Another enabler that was indicated by ten out of 20 interviewed organisations is increasing access to product information. When asked whether the company considers increasing the traceability of its components, interviewee D (CSC 2) stated, "*maybe that digital watermark, I had not thought of it before, but maybe that is a nice idea where you could take away whatever information you want (information about the component)*". Another interviewee (organisation H, CSC 3) mentioned, "*We have tested the identifier into a module*"… "*every single module will be identifiable (with RFID)*". Organisations are considering different approaches how to enable information traceability for MCPs. Information that should be shared is suggested by interviewee L (CSC 5): "*the recycler only needs to know which kind of materials are in the product. If you can give it in detail, it's great, but they just need to know what those (products) contain, is it a bit of silver, or a bit of lead in the soldering. They need to know it in percentage*". Lastly, interviewee S (CSC 6) stated, "*...recycler is better if he can read out which materials are in the product and in what quantities. That is Industry 4.0. I just need a chip somewhere or a code. I then just scan and see the percentage of silver...*". Another way to use the information would be for reuse. Some organisations mentioned that knowing the location of PV modules, history of performance, etc., would ease decision-making on whether it is possible to reuse PV modules.

While upstream CSC organisations are looking at which traceability technology to use for product information, it would be problematic if each of them used a different technology. There is a lack of agreement or standards on what information to disclose, how to disclose it, what technology to use, etc.

Collect data to assess sustainability metrics

One of the constraints in the EU's CSC is the lack of data on sustainability metrics, such as LCA or EPDs. To address this, the EU's PV CSC indicated an enabler, e.g., easing the collection of sustainability-related data. Interviewee G (CSC 1) suggested, "*we have to give them all the raw material or transportation information or process data, but it will be process-specific, concerning energy and carbon footprint. So, it's a huge, a huge amount of data*". While the information is present for the materials producer, it is a question of how to transfer the data. Interviewee R (CSC 6) mentioned, "*We monitor our data; we follow LCA all the steps..*". Interviewee H (CSC 3) also monitors the data: "*in fact, we already did an LCA calculation, it was still a bit of on paper because we don't have a big volume factory*". Nevertheless, for the potential users of the data is a challenge to access it, as interviewee J (CSC 4) stated, "*As far as we know, there are very little available public data like EPDs or LCA-type of data. Currently, that is a challenge being transparent*". Even if organisations collect relevant sustainability data, they do not always make it public or use the same standard. This makes it difficult to collect data and compare it easily.

The data on sustainability metrics is available in many cases. The missing part is implementing one standard to follow and ensuring that the information is accessible. This data could be stored in the product identifier. In the end, it is still challenging to implement it as most of the PV modules arrive outside the EU. Thus, a regulatory approach is needed to encourage organisations to follow a standard or an industry standard that downstream CSC organisations would use in their procurement departments when choosing PV modules by considering sustainability metrics.

Use sustainable positioning as a unique selling proposition

Circular economy suggests that MCPs' lifetime should be prolonged, materials consumption should be reduced, and materials flow should be a closed loop. One way to implement it is through regulations. Another way is for consumers to demand circular products. Sustainable positioning as a unique selling proposition aims to attract customers who have circularity in their minds when choosing which products to buy. Interviewee R (CSC 6) stated, "*I think silicon is CO_2-intensive; the consumption of virgin silicon from China is higher (in CO_2) than the metal purification industry, like aluminium. It's very intensive (silicon CO_2), and with all the CO_2 reduction actions in the world the sourcing of silicon will be threatened to switch to lower CO_2 footprint*". An interviewee from an organisation that uses production waste to produce low CO_2 materials suggested, "*we can take kerf (production waste during wafers production) and make it back to solar grade silicon and you can buy that solar grade silicon,* *so you make a double contract in the way. As more and more companies and more markets appreciate circularity, in particular greenhouse gas emissions, these things are possible. But we are in the very beginning of that, now not well-established*". The industry is in its early steps in terms of circularity. To scale it up, demand is required for circular products. Interviewee A (CSC 2) mentioned, "*it's also something (recycled content in the component) that will be probably part of the sustainability reporting*". The additional demand will be due to the EU's environmental, social, and governance ESG reporting regulations. Another unique sustainability aspect is things like lightweight products; as interviewee H (CSC 3) stated, "*We have a unique selling point that is lightweight*". Lightweight products can reduce material consumption. Most organisations mentioned the demand for low CO_2 products, whether from regulations in specific countries or from customers.

Circularity is promoted by consumers' choices when picking a product with circularity criteria in mind. Organisations innovate to provide products that have lower CO_2 footprints, less toxic materials, etc. Scaling it up would require visibility for products that are more environmentally friendly. But at the moment, organisations are already positioning products that are more circular to gain more sales.

Most mentioned EU PV CSC enablers were discussed. They vary from upstream CSC solutions to improved information exchange and recycler efforts in scaling up activities. These enablers are either being used already or in very early stages within EU PV CSC organisations. Considering the scope is only CSC in the EU, enablers must be implemented by a wider network, such as producers outside the EU. Otherwise, the efforts of EU PV CSC upstream organisations will be of no value, considering most of the MCPs arrive from outside the EU. Thus, enablers need to be adaptable to the whole industry beyond the EU. The whole industry should put some effort into deciding the enablers and how they should be implemented.

3.2.3. Overview of circular economy goals of the European Union's photovoltaics circular supply chain

Using MAXQDA to code relevant sentences related to CE goals resulted in 14 code categories and a total of 72 codes. For specific code categories, not more than one code was taken from each interview. Table 3.3 shows the list of code categories for CE constraints, the number of codes, and the number of circular supply chain stages present in the category.

Table 3.3. List of CE goals in the EU PV industry's CSC (source: made by the author)

	Total number of codes	**Amount of different CSC stages participation (1 to 6)**
Closing the loop	12	5
Reducing carbon footprint	11	5
Expanding European recycling business	7	4
Growing the European solar industry	7	5
Growing the European reuse market	6	2
Reducing the cost per unit	5	4
Changing the European legislation	4	3
Increasing solar industry sales	4	4
Slowing flows	4	2
Producing hazard-free materials	3	2
Narrowing flows	3	2
Digitalising the PV value chain	2	2
Improving industrial ecology activities	2	1
Establishing Circular Products	2	2

The most mentioned CE goals are (1) closing the loop, (2) reducing carbon footprint, (3) expanding the European recycling business, (4) growing the European solar industry, and (5) growing the European reuse market.

Closing the loop

Closing the loop refers to an organisation's ambition to ensure that MCPs are fully recyclable. Interviewee G (CSC 1) gave an example: "*To facilitate 100% circularity of the solar PV value chain*". One way to achieve this goal is to use recycled materials. Interviewee D (CSC 2) stated, "*We are taking it (secondary material) from another industry. We are taking away some product from another industry and upcycling it, giving us a lower carbon footprint*". Another approach is to ensure the recyclability of the product. Interviewee F (CSC 2) said, "*we are fully supportive of the circular concept in the sense that anything comes, that is deployed needs to be able easily disassembled, optimising the use of recovery of any of the materials that are in the components of the PV modules*". Without the goal, motivation or regulations, organisations would not take CE seriously. Interviewee R (CSC 6) stated, "*for us, it's most important is to get the raw materials back from the PV waste and back to different industries*". Interviewee M (CSC 6) said "*Waste to sell the best quality as possible and prepare to transform waste to products. That can be the case, for instance, solar glass. At the end of our process,* *they will be products and not waste anymore*". Recyclers are the ones that can return materials to the loop. But if the product is difficult to recycle, waste is not sorted properly, etc., then there is not much a recycler can do.

Closing the loop refers to using secondary materials, ensuring recyclability, and proper recycling. All CSC organisations are participating in the success of this goal. Each organisation's contribution is required to reach the goal. At the moment, many issues limit the achievability of the goal, as seen from the organisation constraints of the EU's PV CSC.

Reduction of carbon footprint

The reduction of carbon footprint is the second most coded category in CE goals. The goal is related to market demand for sourcing low-CO_2 products. Interviewee J (CSC 4) stated, "*(low CO_2) becomes a sales argument on the European market, especially in the regulated market in France*". Interviewee H (CSC 3) said, "*Low carbon footprint is an essential part"*. Both organisations see low CO_2 MCPs as an important factor in sales. Using secondary materials positively correlates with reducing carbon footprint. Interviewee A (CSC 2) suggested, "*..if we increase secondary cullets percentage, we decrease our carbon emissions"*. Eleven out of 20 organisations at least once mentioned that they see CO_2 reduction as an objective in their business.

The carbon footprint can be reduced solely by organisations by, for example, using renewable energy. It becomes difficult to decrease the carbon footprint further as most emissions usually occur in the rest of the circular supply chain. In these cases, organisations need to select suppliers that have low CO_2 materials and components or ensure that their MCPs are recycled with low CO_2 recycling processes.

Expansion of the European recycling business

Increased circularity in the industry has the potential to benefit CSC organisations. Upstream CSC organisations could have a higher amount of secondary materials to choose from. In the case of the EU, it means potentially more stable materials prices, as the EU imports large amounts of various materials. Thus, if it were possible to source locally from the EU's secondary materials, there would be higher resilience in material prices. Downstream CSC organisations can develop new circular business models and increase repairability, reusability or recyclability. Interviewee G (CSC 1) mentioned, "*...we would go in joint ventures or in partnerships with companies that could extract the silicon cells, and then, we would take solar cells ourselves and recycle them depending on how clean the cells are*". It is difficult to scale up secondary materials usage when there is a lack of recyclers, meaning close collaborations need to be established at the start. Interviewee H (CSC 3) also cooperates closely with another organisation for circularity purposes: "*We have a partnership with our partner (material producer) that could use recycled plastics or bio-based polymers*". Interviewee U (CSC 6), a recycler, suggested, "*by 2030, we want to have at least 400 (PV recycling) plants, simply to be able to manage a sheer mass (of forecasted PV waste). I think we will only be able to cover 30% of the market…*". In the next 5–10 years, due to exponential PV waste accumulation in the EU, it will be inevitable to establish recycling plants. The sooner it is done, the faster feedback can travel within CSC in terms of how to improve the design of MCPs, collection, sorting, etc.

The expansion of the EU's recycling business can offer multiple benefits for EU PV CSC organisations, from increased amounts of secondary materials to new business cases for downstream CSC organisations. This goal is shared by multiple CSC stages; thus, organisations in upstream CSC are willing to invest resources in easing downstream CSC organisations' processes to handle all of the PV module waste in the future.

Growth of the European solar industry

The EU's PV industry is insignificant if to compare the amounts produced versus imported. Most PV products are imported; thus, naturally, one CE goal is to have higher local production to develop circular processes. It is difficult to understand what MCP design changes are needed for higher circularity if there is a lack of these businesses in the EU. It requires effort to analyse the upstream supply chain, and if it is outside the EU, it becomes more difficult to do so. Interviewee G (CSC 1), who uses PV production waste as a source for producing PV materials, stated, "*We are in the process of looking at the important projects of common European interest (IPCEI) initiative in the EU*". The initiative funds highly important industries in the EU. A representative of a components manufacturer E (CSC 2) stated, "*the main goal is to have more partners not from Asia but from European companies because silicon wafer (PV sub-component) produced in Europe has much lower carbon footprint compared to the Asian silicon wafer*". To reach low CO_2 targets, it is also to produce locally, especially if it can lower CO_2 emissions when the same component made in other regions has higher emissions.

The growth of the European solar industry, especially the upstream part of it, contributes to circularity objectives. The goal is shared both by upstream and downstream CSC organisations. Dependency on other regions' production might limit opportunities to investigate what could be changed for circularity purposes in upstream CSC organisations.

Growth of the European reuse market

The reuse market in the EU refers to reusing PV modules that are still working after their first usage. It can also refer to defective modules from PV manufacturers. This goal is only mentioned by CSC stages 5 and 6 by organisations that manage EoL or recycle PV modules. Naturally, upstream CSC has no interest in their products being reused as customers will buy fewer new products. Interviewee O (CSC 5) stated, "*We have been setting this up for a good two years (business to inspect and reuse old PV modules). Now, I am the project manager for the further development of this area. And now we are slowly reaching a crossroads where we see that this is a nice business area, and we have to continue to build it up, continue to invest*". Interviewee who reuses PV modules (organisation N, CSC 5) said, "*we are talking about several megawatts (~10 000 PV modules) of modules that are not all in one plant*". They source PV modules from different PV modules, inspect them and sell it to Africa where any amount of electricity is needed. Interviewee P (CSC 5) suggested, "*in order to get these illegal markets (illegal shipment of EoL PV modules outside EU) out, to filter the quality, the manufacturers must join in at some point. And I hope that at some point the manufacturers will be so far advanced that they will also check for reuse and perhaps set up a second-hand market*". Simple traceability of each PV module could allow for tracing back illegally shipped PV modules to determine at which stage, whether collector, recycler or PV system user, the PV module left the EU's PV CSC. Representative of recycling company R (CSC 6) stated, "*we are also required by law to inspect the modules beforehand if it is economically reasonable. And that's why we have now bought a test facility...*" It is difficult for a recycling party to undertake an inspection for reuse as CE constraints show that most PV modules that arrive at the recycling facility are already damaged. The reuse market delays the amount of waste that will go to the recycler. For recyclers, they need 5,000–10,000 tons of PV waste to run recycling plants. The recyclers could receive higher amounts of waste by stopping illegal shipments of PV waste.

The five most coded CE goals were discussed. The reduction of carbon footprint can be categorised as something that can be achieved, to some extent, by organisations alone. The other four CE goals require the cooperation of CSC organisations. The goals of organisations are linked with the need for cooperation, which is now lacking. EU PV CSC organisations share similar goals, and each goal contributes to the success of the whole CSC.

3.2.4. Discussion of the constraints, enablers, and goals

To ensure the reliability of identified constraints, enablers, and goals from the EU's PV industry, a comparison of results is required with similar studies.

Table 3.4 shows whether there is a link between the outcomes of identified CE constraints (barriers), enablers, and goals and other research related to the PV industry. Notably, most of the research did not include direct communication with PV organisations; thus, researchers did not match concrete barriers, enablers or goals with specifics of organisations within the PV industry.

Almost all of the identified constraints from this research can be found in other researcher efforts that derive the constraints usually not directly from PV organisations but from other sources/methods, such as analysing data or specific projects/models. Half of the enablers can be found in other research. As this study analysed transcripts of each interviewee of the EU PV organisations, there were concrete suggestions from interviewees for solving one or another problem in a specific way.

Table 3.4. Comparison of result reliability against other researcher (source: composed by the author based on a literature review)

CE constraint categories	**References in other studies that match identified PV circularity constraints, enablers, and goals**
1. Unpredictable volumes for reuse and recycling	Franco & Groesser, 2021; Mathur et al., 2020; Tsanakas et al., 2020
2. Insufficient value chain collaboration	Franco & Groesser, 2021; Rabaia et al., 2022
3. Insufficient purity of recyclates for reinsertion in PV production	Franco & Groesser, 2021
4. Uncoordinated legislation over Europe	Franco & Groesser, 2021; Rabaia et al., 2022
5. Hesitant exchange of information	Franco & Groesser, 2021; Rabaia et al., 2022; Boukhatmi et al., 2023
6. Insufficient traceability of PV modules	Franco & Groesser, 2021; Boukhatmi et al., 2023
7. Immature recycling methods often result in downcycling	Franco & Groesser, 2021; Rabaia et al., 2022; Mathur et al., 2020
8. Illegal PV module exports	Boukhatmi et al., 2023
9. Underdeveloped reverse supply chain	Franco & Groesser, 2021; Rabaia et al., 2022; Tsanakas et al., 2020; Mathur et al., 2020

Continued Table 3.4

CE Constraints categories	References in other studies that match identified PV circularity constraints, enablers and goals
10. Conventional PV recycling is not profitable yet	Franco & Groesser, 2021
11. Changing materials inserted in PV production over time	Franco & Groesser, 2021
12. Low-risk appetite for investments in industrial-scale recycling	Franco & Groesser, 2021
13. Underdeveloped regulatory frameworks	Franco & Groesser, 2021
14. Cheap virgin raw materials	Franco & Groesser, 2021
15. Missing PV module design for circularity	Franco & Groesser, 2021; Rabaia et al., 2022
16. Poor viability of circular business models	Franco & Groesser, 2021; Rabaia et al., 2022; Tsanakas et al., 2020
17. Strong competition from non-European countries	-
18. Difficult access to external byproducts	-
19. Underdeveloped secondary material markets	Franco & Groesser, 2021
20. Fluctuating supply of byproducts	-
List of CE enablers	-
1. Implement internal and third-party certifications/standardisation	Rabaia et al., 2022
2. Scale up industrial recycling	Rabaia et al., 2022; Tsanakas et al., 2020
3. Increase access to product information	Boukhatmi et al., 2023
4. Collect data to assess sustainability metrics (LCA/EPD)	Rabaia et al., 2022
5. Use sustainable positioning as a unique selling proposition	-
6. Exploit rising market interest in sustainable products	-
7. Engage in PV panel design for circularity	Tsanakas et al., 2020
8. Increase collaboration with recyclers	Rabaia et al., 2022
9. Engage in pilot projects	-
10. Engage in collaboration with plant owner/collection schemes	Boukhatmi et al., 2023

Continued Table 3.4

CE Constraints categories	**References in other studies that match identified PV circularity constraints, enablers and goals**
11. Engage in the EU's PV industry standards and regulations	-
12. Recover solar materials in high-quality	Mathur et al., 2020
13. Establish the EU reuse market	Tsanakas et al., 2020; Boukhatmi et al., 2023
14. Increase traceability	Boukhatmi et al., 2023
15. Share information with customers to prove sustainable products	-
16. Exploit the potential of reuse as a profitable business model	(Rabaia et al., 2022)
17. Build up testing and repurposing infrastructure for PVs	-
18. Use of product identifier	Boukhatmi et al., 2023
19. Reinsert internal production waste	Bartie et al., 2021
20. Collaborate with academia to test and prove recyclates	(Rabaia et al., 2022
21. Create economic value	-
22. Sell recycling technology/as a service	-
23. Assign EoL responsibility to producers	-
24. Monitor PV performance during usage	-
25. Establish benchmarking among European PV producers	-
26. Intensify quality control measures	-
27. Reinsert external production waste	-
28. Reduce virgin raw material consumption	Rabaia et al., 2022
29. Engage in lobbying activities	-
CE goals	-
1. Closing the loop	Rabaia et al., 2022
2. Reduction of carbon footprint	Rabaia et al., 2022
3. Expansion of European recycling business	Rabaia et al., 2022
4. Growth of the European solar industry	-
5. Growth of the European reuse market	Rabaia et al., 2022
6. Reduction of cost per unit	Rabaia et al., 2022

End of Table 3.4

CE Constraints categories	References in other studies that match identified PV circularity constraints, enablers and goals
7. Change of European legislation	Rabaia et al., 2022
8. Increase in solar industry sales	Rabaia et al., 2022
9. Slowing flows	-
10. Production of hazard-free materials	Rabaia et al., 2022
11. Narrowing flows	Rabaia et al., 2022
12. Digitalise the PV value chain	Rabaia et al., 2022, Bartie et al., 2021
13. Improvement of industrial ecology activities	Rabaia et al., 2022
14. Establishment of circular products	Tsanakas et al., 2020

As other research lacked feedback directly from PV organisations, the list of potential solutions is larger in this study. CE goals in the PV industry in other research are derived indirectly from the PV industry's standpoint on issues the industry should address rather than from PV organisations.

The findings in this study are similar to those of other research. The main difference is that this study is based on a direct information source, e.g., the EU PV organisations. It allows for connecting specific PV organisations with CE barriers, enablers, and goals. Additionally, concrete reasoning behind the connections is established, such as why exactly one or another constraint is important for EU PV organisations, how it affects their operations, etc.

3.3. Results of weighting indicators for the European Union's photovoltaics circular supply chain

Two Delphi rounds were conducted. Within the first round, experts identified that two indicators were not relevant for the PV industry: (1) renewable content in the product and (2) recirculation of materials, components, and products in the biological cycle. For these indicators to be relevant, the industry needs to use renewable or biological content, such as wood. In PV modules, these materials are not used; thus, these two indicators were eliminated after the first round. The ranking values of the first round for those two indicators were removed. Table 3.5 shows the summary of the two rounds.

Table 3.5. Summary of Delphi rounds

Indicators	Round 1 weights	Round 2 weights
Reuse content in the product	10.3%	8.86%
Amount of recycled content in the product	12.4%	12.89%
Lifetime of materials, components, and products	17.2%	18.91%
Reuse content in the product at the end-of-life	18.3%	21.82%
Recycling rate of the product	20.7%	21.82%
Constraint's impact on the organisation's CE potential	11.9%	8.60%
Interest in investing resources in solving the constraint	9.1%	7.09%
W coefficient (0 – no agreement, 1 – full agreement)	0.30	0.72

1.3.1. Delphi round one results

In each round, experts provided comments to support their ranking choice. These comments will be discussed in the following sections.

Reuse content

Expert F stated, "*difficult to see material reuse being very practical given logistics of PV end of life*". While most PV modules are damaged during demounting and transportation, during the EoL stage, PV modules can be reused. The reuse of separate components is difficult as the PV industry constantly improves and changes component functionality, dimensions, etc. Expert D mentioned that it is "*difficult to achieve with long warranties of new modules*". With PV modules lasting for 20–30 years, it may be challenging to find applications for old PV modules that will have less power than the new ones. Expert A stated, "*reuse content in the product is not a priority, with the exception of production scrap. This is due to expected changes in technologies and formats, which impede reuse of the components or materials in the production of new PV modules without any prior processing*". The expert identified the issue precisely: old components would not fit in the new PV module design. However, the product, the whole PV module, could be reused.

Recycled content

Expert D commented that it "*can be important with rare and conflict materials certificates of origin*". Additionally, expert A suggested that "*the amount of recycled content in the project needs to gradually increase as recycling/upcycling routes become more mature (which will happen when EoL volumes increase). Of key importance will be the integration of recycled Si (from kerfs, production scrap and EoL)*". It is difficult to increase the recycled content if there are no streams of secondary materials available. Thus, recycling needs to be improved first.

Lifetime of materials, components, and products

Expert F stated that "*the longer modules stay in service, the lower the need for recycling*". The comment suggests that one of the highest priorities is to ensure longevity together with reuse. Expert D suggested that a "*long lifetime is desirable but may be in conflict with cheaper, less resource intensive modules but lower lifetimes, rapid progress in module power*". The comment suggests that perhaps it is better to design or replace modules rather than keep them operational for a long time. In those cases, the value generated by the new product should be higher than the old PV module's performance, plus the economic and environmental costs of recycling it. Expert B pointed out the "*lifetime as the most relevant indicator for the buyer (long usage avoids waste)*". In this scenario, longevity might allow for delaying recycling costs. Expert A suggested that the "*lifetime (together with quality and efficiency) of the product (PV module) is one of the most important indicators to improve sustainability and circularity; this is backed up by recent scenario simulations and studies such as Mirletz et al. (2022)*". The expert suggested that longevity should go toe to toe with the product performance; otherwise, the lower performance of the product will lead to its replacement.

Reused content from the outflow in materials, components, and products

Expert D stated that "*extension of the lifetime of components, reuse, and repair potential will save resources and energy*". Whereas expert E indicated the "*lack of information on the EoL material*". The lack of information results in the components having unknown functionality, performance, purity, material content, etc. In these cases, it is difficult to find applications for the components and sometimes for the PV module itself. Expert C commented that "from a circular economy's point of view, keeping components at a high level of functionality is the first aim, although for PV, I know this is difficult, and recycling may be the easier option". Indeed, with old components that have no traceability of information and with rapidly improving PV technologies, it is difficult to implement reuse strategies for the product. Expert A stated that "*Reuse of the full product (PV module) for second-life applications is also a solid route to improve circularity (not including the* *reuse of components and materials, which is normally not feasible due to changes in technology and formats over the decades of lifetime)*". Realistically, only PV modules themselves could be reused.

Recycling rate of materials, components, and products

Expert F suggested that "*A high recycling rate would be an indicator that we have (a) gotten recycling economics to be competitive with other end-of-life management options, (b) that logistics have been streamlined, and (c) that we have achieved a more uniform policy signal to drive recycling*". A successful recycling of PV modules requires scaling, proper logistics and uniform policy in the EU. Expert D stated that it is "*necessary to fulfil legal requirements, harmonisation is required*". According to EU regulations, PV modules should be recycled to a certain extent. However, for that, additional harmonisation of regulations is required as they differ in each country. Expert E suggested that "*the zero waste society will become more important, both due to waste and resource management*". Regarding resource management, expert A also highlighted the importance of introducing materials back "*once first and second life are expired, the next viable route is to recycle the product with the highest possible rate to recover the most massive (glass, aluminium) and valuable (Ag, Si) materials within*". Recycling activity should be the last resort for any product. For effective recycling, it is essential to have the scale of economies to reduce recycling costs and enable highly efficient recycling equipment to generate as pure as possible secondary materials.

Impact of constraints on the organisation's Circular Economy potential

Expert F stated that "*we are seeing more progressive, brand-oriented developers increasingly make end-of-life commitments in partnership with recyclers, a positive development (especially in the US where there is no PV end-of-life policy framework*". There are some activities within the EU's PV industry to address constraints in cooperation between recycler and plant owners. Expert D suggested that it "*could be included in sustainability analysis in the future and could be a potential USP (unique selling point) at equal prices*". A sustainability analysis, such as the double materiality analysis, could be used to measure more precisely how these constraints affect single organisations. On the opposite side, expert E mentioned that "*incentives and legislation, e.g., the EU taxonomy, must be used more to steer the industry towards enhanced sustainability*". While it is sometimes difficult to understand the impact of CE constraints on standalone organisations, the expert suggests industry policy implementation for measuring and potentially solving the constraints. Expert A stated that "*all ten identified constraints have a large impact on the circular economy potential of the PV sector, in particular, a more uniform legislative framework across Europe would be very useful to reach* *standardised procedures and reduce costs associated with collection and logistics*". The impact that organisations feel from the constraints should be addressed with EU policy, as it is unlikely that organisations themselves will come up with solutions in the highly competitive industry.

Interest in investing resources in solving the constraint

Expert D stated that "*shrinking material values and small waste streams do currently hinder significant investments*". From a business opportunities perspective, it is challenging to realise a business model related to recycling when raw material prices are low. Additionally, the waste stream from the PV sector is relatively low at the moment, and the volumes will kick in exponentially starting around 2023. Expert E suggests that "*logistics has been the main hurdle so far*". In reverse logistics, where end-of-life PV modules are damaged, it is difficult to implement reusability.

The first round results show various views that experts have on the issues. The first round resulted in a W coefficient of 0.30, which is a moderate agreement between the experts. Zero would indicate no agreement, and one would mean there is 100% consent between the experts.

1.3.2. Delphi round two results

For the second round, experts received averages of each indicator ranking. Additionally, they received comments from other experts on the indicators. The second round of findings is discussed below.

Reuse content

Expert A stated that "*not so feasible in PV as components cannot normally be reused without processing*". Indeed, old glass or frames might not meet the current standards that the PV industry uses. Expert D suggested that "*According to product warranties and updated specifications, the reuse potential in new modules will be difficult to achieve*". Furthermore, expert F commented that "*as a general matter, I do not believe that direct reuse of components into new modules will ever be practical from a cost/logistics/technology evolution perspective*". All of the experts generally agree that it is difficult to produce a PV module with old components.

Table 3.6. Expert ranking for the "reuse content" indicator

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	6	7	6	5	6	2

The reuse strategy is difficult to implement in the PV industry, as seen in Table 3.6, which shows the expert ranking values for the "reuse content" indicator from 1 (highest importance) to 7 (least importance).

Recycled content

Expert A suggested that "*including recycling content in PV modules (either originating from PV industry or others) is a good indicator to show a reduction of primary raw materials, especially for critical ones*". Expert D stated that the "*amount of recycled content may be important for certificates of origin, mitigation of critical and rare material use*". Additionally, expert F comments that "*while the use of recycled content in PV is desirable, it will likely only be practical for certain elements' primarily metals*".

Table 3.7. Expert ranking for the "recycled content" indicator

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	4	1	4	4	4	5

Driving beneficial reuse overall has greater priority and benefit. One exception is if we can solve the logistics and technology hurdles to recycle solar glass, it could have a significant environmental benefit. Lastly, expert C stated that "*recycling competes with reuse, and in practice, the cheapest rouse is the preferred one*".

Experts generally agree that recycled content indicators are relevant to PV CSC organisations. It can potentially reduce environmental impact and reduce raw materials consumption. See the distribution of recycling content ranking from the experts in Table 3.7.

Lifetime of materials, components, and products

Expert A suggested that "*even replacing by less resource-intensive and higher-efficiency modules has been proven to be more energy consuming and material consuming that employing long lifetime modules. Longer lifetime and high quality represent the most sustainable route*". Expert D stated that "*a long service time is desirable from a life cycle point of view though commercial interest may conflict with this (repowering because of higher efficiency)*". Additionally, expert F commented that "*ideally longer productive module lifetime would (a) spread the impact of manufacturing the panel over more kilowatt-hours, lowering the impact per unit of energy and (b) reduce the demand for EoL management. Improvements in module performance/efficiency could well overpower module longevity and drive repowering/module retirements before module fail, undermining the value of longevity*".

Lastly, expert C stated that "*durability for components is important, as designs for disassembly*".

Table 3.8. Expert ranking for the "lifetime of materials, components, and products" indicator

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	1	4	3	1	3	3

Experts agree on likely scenarios of replacing operational PV modules with newer, more efficient ones. On the other side, keeping an older module working would have less impact on resource usage. Table 3.8 shows the ranking provided by each expert.

Reused content from outflow in materials, components, and products

Expert A stated that *"reuse products as long as possible to further extend lifetime is reasonable. For example, if modules are replaced before reaching EoL, for re-powering due to economic reasons, these modules should be reused in a different site/application to maximise sustainability"*. Expert D commented that *"reuse and repair can extend the lifetime of a PV module but is currently borderline concerning economics"*. Expert F suggested that it "*relates directly to the rating of recycling. The higher the rate of material recovery/beneficial reuse, the better the economics of recycling/EoL*". Lastly, expert C suggested that "*keeping functionality is the first aim, even though I'm aware this is challenging for PV*".

Table 3.9. Expert ranking for the "reused content from outflow in materials, components, and products" indicator

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	2	3	2	3	2	1

Experts have a similar vision, which is that it is possible to reuse PV modules to extend their lifetime. However, the economic and technical challenges for inspection or repair limit reusability. Table 3.9 shows rankings provided by the experts for the "reused content from outflow in materials, components, and products" indicator.

Recycling rate of materials, components and products

Expert A suggested that "*simulations show that long lifetime modules are more sustainable than highly recyclable modules. The priority should be developing lifetime* *high-efficiency and high-quality modules before developing recycling processes, which is also very important, but we have still some years to develop the processes before waste volumes become significant*". Expert D stated that "*valuable resources should be saved and reutilised not only in PV but also in other industries, especially in Europe with a poor raw material supply*". Lastly, expert F suggested that "*a high recycling rate would mean either policy or economics-made recycling the best choice, and part of those economics would be greater material economically beneficial reuse*". Experts have different views on recyclability.

Table 3.10. Expert ranking for the "recycling rate of materials, components, and products"

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	3	2	1	2	1	4

The first expert suggested that policy instruments are fundamental for the PV industry to solve circularity issues. Other experts have suggested that recycling is already regulated in the EU, although its effectiveness is questionable due to the low quality of recycled materials and waste shipments outside the EU.

While it is not the first option to consider, it is difficult to implement it as it requires policy instruments or good enough economic conditions. Table 3.10 shows the rankings of the experts on the "recycling rate of materials, components, and products" indicator.

Impact of constraints on the organisation's Circular Economy potential

Expert A stated that "*collection and logistics need to be improved. Delocalised recycling and re-manufacturing are desirable*". Additionally, expert D commented that "*environmental factors might gain relevance comparing different brands at the same price. Local content and environmental factors could be used to support domestic producers*". The impact on PV organisations is mostly related to logistics and opportunities for improving local EU content with recycled materials.

Table 3.11. Expert rankings for the "impact of constraints on the organisation's CE potential" indicator

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	5	6	5	6	5	6

Table 3.11 shows the rankings provided by experts on the "impact of constraints on the organisation's CE potential" indicator. Generally, the impact of CE constraints on PV organisations' business models may be quite low as few companies conduct high-value recycling or reuse PV modules with proper testing procedures.

Interest in investing resources in solving the constraint

Expert A commented that "*large advances can be made at the moment through policy updates. Investment will follow*". Additionally, expert D stated that "*recycling is mandatory in Europe, and large waste streams are expected in 2030*".

Table 3.12. Expert rankings of the "interest in investing resources in solving the constraint" indicator

Expert	Expert A	Expert E	Expert D	Expert F	Expert B	Expert C
Rank (1–7)	7	5	7	7	7	7

The first expert suggested that policy instruments are fundamental for the PV industry to solve circularity issues. Other experts suggest that recycling is already regulated in the EU, although its effectiveness is questionable due to the low quality of recycled materials and waste shipments outside the EU. Table 3.12 shows expert rankings for the "interest in investing resources in solving the constraint" indicator.

The Delphi method allowed for ranking indicators based on their relevance for the PV industry through two rounds. The first round concluded with a W coefficient of 0.30, whereas the second round concluded with a 0.72 W coefficient. A strong agreement was reached after the second round. Expert comments for the second round demonstrate a higher focus on specifics of the PV industry. It shows that expert views have synchronised due to reading other experts' comments from round 1.

3.4. Results of input collection from organisations of the European Union's photovoltaics circular supply chain

Inputs were collected from 12 organisations. The inputs were based on the organisation's perceptions, whether a constraint's impact on the indicator ranged from 1 (very low impact) to up to 5 (very high impact). The summary of the results is shown in Table 3.13.

Table 3.13. Summary of inputs from the EU PV organisations on their perceptions of how constraints affect indicators

Results of inputs collection	Reuse content	Recycled content	Lifetime	Expected reuse	Recycling	Impact	Interest
Unpredictable volumes for reuse and recycling	2.77	3.60	1.90	3.63	3.57	3.07	3.04
Insufficient value chain collaboration	2.20	3.04	2.20	2.30	2.96	2.00	2.57
Uncoordinated Legislation in Europe	2.70	3.13	2.20	3.43	3.33	3.20	2.73
Insufficient purity of recyclates for reinsertion in PV products	2.00	3.67	2.07	1.80	4.10	3.17	3.47
Hesitant exchange of information	3.13	3.87	3.40	3.43	4.00	3.20	3.50
Insufficient traceability of PV modules	2.80	2.63	3.80	3.70	3.25	3.20	3.30
Immature recycling methods often result in down-cycling	1.87	2.97	1.37	1.43	4.23	2.93	3.13
Illegal end-of-life PV module exports to non-European countries	3.23	3.90	2.40	3.43	3.30	3.47	3.57
Poor logistics handling in the reverse supply chain	3.00	2.97	3.20	3.63	2.83	3.17	2.57
Conventional PV recycling is hardly profitable	2.00	3.67	2.13	2.13	4.08	2.96	1.83

Organisations were also asked to comment on the reasoning on which they based their inputs. The comments will be discussed from the 1st to 6th CSC stage.

Circular supply chain stage of 3rd, 4th, ..., tier suppliers

There was only one organisation from the first circular supply chain stage. The reason is that the EU has few producers of silicon or other raw materials. Interviewee H, representing a silicon producer in Europe, stated that "*you cannot reuse (end-of-life) silicon*". Further, the interviewee elaborated that "*recycled silicon should be of a consistent flow that would be inserted in polysilicon production. No sorting would be possible for specific customers"*. The issue is that the interviewee organisation could not produce materials in batches. They would require huge amounts of silicon, which is not possible with the current waste stream. Additionally, the issue is that there is "*no solution to mix secondary silicon with virgin silicon"*. While it is possible to develop a mixing solution, the costs and lack of waste are not there. While there is recycled silicon available in 99.99 purity (PV solar grade silicon requirement is 99.99999), another issue is present, as interviewee H suggested, "*metallurgical grade silicon requires a specific catalyst, purse silicon, such as 4N (99.99%) purity, would not be compatible with our process*". Since there is no knowledge from the interviewee organisation on CE constraints and how they could impact CSC stage 1, the first stage is not included in the input collection.

1st and 2nd tier suppliers

Interviewee B, representing a plastic components manufacturer, stated that "*you cannot reuse encapsulants or silicone*", which makes the indicator of "reuse content" irrelevant to them. Additionally, interviewee B suggested that "*silicon and encapsulant are very low of value compared to other PV module components value*". Recycling pathways might not be feasible for low-value components. On the other hand, they had not experimented with it, as interviewee B commented, "*if we start talking to PV recyclers for the collection of our materials, it would probably be possible*". The plastic should be of high purity/quality, which is difficult now to obtain; as interviewee B elaborated, "*it is difficult to get high-quality recycled plastics*". Furthermore, interviewee B stated that "*some manufacturers declare they use POE, although its EVA materials inside the encapsulation*". This might hinder longevity and recyclability; thus, more extensive information sharing and traceability are important for the interviewee organisation.

Interviewee F, a representative of solar cells manufacturing company, stated that "*it is not possible to reuse solar cells*". Since solar cells are encapsulated with a polymer that works as an adhesive, it is not possible to dismantle cells, which makes reuse content indicator irrelevant for them. In terms of recycled content, interviewee F suggested that "*silicon is the main issue in terms of how to purify* *it"*. End-of-life silicon contains dopants boron or phosphorus that need to be removed, which is hardly possible in an economical way. In regards to lifetime interviewee, F commented that it "*depends on how the solar cells are encapsulated, whether its glass-glass, glass-back sheet, what encapsulation is used*". The longevity of cells depends mostly on the technology used by PV module manufacturers. In some cases, it might be possible to reuse intact solar cells, as interviewee F suggested, "*on some designs, such as NICE, it would be possible*". NICE refers to an innovative encapsulation method which, instead of polymer-based encapsulation, uses vacuum and sealant around PV module edges. It results in the possibility of dismantling PV modules without damaging the solar cells. Generally, interviewee F mentioned that "*there is a very low amount of PV upstream value chain in EU*", which results in low innovation potential for circularity.

Interviewee M, representing an ingot and wafer-production company, stated, "*Due to the lack of manufacturing in the EU, it might be difficult to establish recycling factories. You need to add very strong traceability of each of the components as it comes mostly from China*". Recyclers would benefit from knowing what PV modules consist of and who made them, but in any case, it will not be enough as Interviewee M suggested, "*recyclers will still need to deal with old PV modules that has no information on what these modules are made of*". While some organisations attempt to contact manufacturers for this information, it is difficult to get high-quality data when products are manufactured in China or when PV producers have ceased to exist. Interviewee M saw low chances of value chain collaboration: "*it could change in the future, the formats of the modules. Chinese are working as a "cartel" to decide the sizes of modules, cells, etc. Due to glass manufacturing capabilities PV modules have already standardised width*". With China's dominant influence in PV manufacturing, the EU's interest in circularity collaborations might not be heard if it includes additional costs or efforts for the Chinese PV companies.

Product manufacturers

Interviewee G, representing a PV module manufacturer, stated that *"(recycled content) could allow to reduce materials consumption if manufacturers would be obliged to use a specific amount of reuse content*". Additionally, regarding poor logistics in the reverse supply chain, interviewee G mentioned that "*when you recycle glass, you shred it into cullets anyway, it has no impact*". Glass has a low impact on how EoL PV modules are handled. Interviewee G mentioned issues in information exchange within the industry: "*it is way harder to trace Chinese products than to trace EU products*". It could be difficult to implement information flow when the overwhelming majority of PV modules are made in China. Additionally, interviewee G said, "*we do not have issues in sharing our data with partners*". One way to address it is, as interviewee G commented: "*if the European Commission* *would make it obligatory to show all materials that are in the product, then we would do it*". Interviewee G also commented on recycling issues of PV modules: "*the European Commission should suggest a solution, not the manufacturer*". With a generally low impact and interest from EU PV CSC organisations in solving the constraint, there may be no other option than the involvement of more policies to regulate the EoL management of PV modules.

Interviewee E, representing another PV production company, stated that "*standardised usage of second-hand PV modules should be covered by regulations*". Additionally, interviewee E stated that "*proper testing for second-hand PV modules would increase costs; thus, fewer PV modules would be reused*". While the PV industry reuses PV modules with questionable testing procedures or no testing at all to know safety and other parameters, regulation should be implemented to govern the activity. While recycled content is generally possible to be increased for PV modules, interviewee E raised a "*question in price and quality of recycled materials for reinsertion in PV production*". Interviewee E suggested a way to address it: "*higher volumes would end up at recyclers (if illegal PV EoL shipment is prevented from EU), then they in the future would recycle PV modules with high efficiency/good recyclates quality*". On the other hand, the organisation of interviewee E saw that the recycling rate was more relevant than for PV module producers because "…*producer takes into account more factors, such as the price for secondary materials*". Recyclers can realise secondary materials in various industries, whereas, for PV module producers and further upstream value chain members, it is a question mark of whether they can compete with virgin raw material price and quality.

Usage

Interviewee A, a representative of one of the largest EU PV module distributors and developers, stated that "*reuse of PV modules is being suggested as standard in IEC (International Electrotechnical Commission)*". Currently, there is too much freedom to sell second-hand PV modules without minimal testing. Furthermore, interviewee A suggested that unpredictable volumes for reuse and recycling would "*impact our possible new business models*". There is an economic incentive to reuse PV modules as they can be sold for the second-hand market. However, with difficulties in forecasting waste streams, it can be risky for investment options in testing equipment that would require high volumes of EoL PV modules. From the perspective of a middleman between the PV producers and end-users, interviewee A commented that "*it would be nice to buy PV modules that have higher recycled content*". The question remains to which extent customers would be willing to pay extra for higher recycled content.

End-of-Life management

Interviewee D, representing an organisation that collects and inspects PV modules for reuse and recycling, stated that "*there is a lack of standardisation within the PV value chain on component sizes, dimensions, etc.*". While it is true, considering over 100,000 unique PV modules in the global market, it is difficult to standardise with rapidly evolving PV technologies. On the topic of traceability, interviewee D suggested that "*it is currently not possible to determine who manufactured the PV module, what is the composition of modules, etc. Now it is limited to labels if present on PV module, barcodes are not readable*". A lack of information access on the PV modules hinders the chances of circularity actions. Regarding the European legislation, Interviewee D agreed that there is confusion and a lack of standardisation of how EU countries distribute waste; for example, in France, a tender is organised every five years for recycling PV waste. As for the reverse logistics, interviewee D stated that "*from 500 modules, one pallet (~30 modules) might be interesting for reuse for spare parts*". Due to damaged modules and outdated components, it may still be possible to reuse at least some parts. In the case of Germany, interviewee D suggested that "*every city (in Germany) has a collection point where PV modules can be put into containers in Germany*". The issue with the system is that, as mentioned by the interviewee, up to 99% of PV modules are damaged and cannot be reused. Furthermore, interviewee D suggested that "*above 300 Wp module power for reuse is possible*". As of 2024, the residential segment PV module's power ranges from 410 to 430 Wp, whereas ~10 years ago, it was ~ 250-300 Wp. The interviewee pointed out that very old modules might not find market applications for second-hand usage. There are still some technical constraints, as interviewee D stated, regarding reusing whole modules: "*there is no solution for testing a large amount of PV modules for second-hand applications*". On a similar topic, interviewee D stated that "*after 10–12 years, you can repower utility-scale system in the economic sense*". Due to rapidly increasing PV module power, there is already an incentive to replace PV modules that did not even reach the middle of their warranty period. On the illegal EoL shipments outside the EU, interviewee D stated that "*if we send EoL modules to Africa, we lose the materials*". Additionally, interviewee D commented that "*when we can earn higher value from recycled materials, then it might be better to recycle than to reuse*". Old PV modules have a larger silver content, for instance; thus, in some cases, recycling might be better from an environmental and economic sense than keeping it running at low power capacity.

Interviewee K, representing a company that maintains PV parks and reuses PV modules, stated, "*Sometimes, we have access to waste accumulation to find out why they are defective or not working. We saw very small issues in the backsheets, very tiny. There must be traceability of why the modules are dismantled*". If data is provided to reuse companies on reasons for the failure of PV modules, reuse or repair activities would be improved. Furthermore, interviewee K suggested that "*we have* *some modules that we do not know which cables, which junction box is used. A bit of a nightmare for repair when we have no information. Zero information on the backsheet*". The hesitant exchange of information limits the interviewee's K organisation from scaling up its repair or reuse business operations. Responding to the question of whether the organisation felt an impact or was interested in solving constraints, interviewee K stated, "*we have created a big database of modules which are installed in France*". Additionally, interviewee K commented on poor logistics handling in the reverse supply chain: "*Big problem, but we solved it. We do it ourselves the dismantling, we ensure there is no damage during reverse logistics*". The organisation is solving its issues due to a lack of access to information and damage caused by the dismantling/transportation of EoL PV modules.

Recycling

Interviewee J, representing a PV module recycling company, commented on unpredictable volumes for reuse and recycling: "*it is something we are aware of. I think that's why it comes to value chain collaboration and legislation over Europe. We have to be part of those stakeholders*". The interviewee's point of view is that organisations from the PV value chain need to be more involved in shaping policies. As regards the current situation, interviewee J stated, "*right now, we have large stock to treat (PV module waste), we don't have enough capacity. We don't have enough storage*". Additionally, the interviewee mentioned that it is for a short period. When they process the waste, there is a high risk of the facility running on low capacity due to difficulties in forecasting PV waste. As regards the profitability constraint of conventional PV recycling, interviewee J suggested that "*we have proven it is profitable*". But still, they charge clients for recycling, taking less from waste organisations, and placing higher gate-fee costs for utility-scale or small batches. Due to the specifics of their recycling process, interviewee J stated, "*for us, it is not critical if PV modules are damaged*". The condition of PV modules at EoL does not impact the quality of recycled materials after their process. Additionally, interviewee J mentioned: "*for us, it is better new PV modules, their quality is higher*". The business case for them is higher with newer modules as they can recover higher-quality materials. On the other hand, older PV modules have more silver, which is the main valuable material within PV modules.

Interviewee L, representing a company that recycles PV modules, stated: "*There are three main organisations and 50 additional ones that implement extended producer responsibility (EPR) in Germany for PV modules. Everyone in Germany looks for the cheapest EPR solution*". Furthermore, interviewee L commented: "*In France, it is easier when only one player is responsible for that*". Different regulations in each country limit recycler options for securing large amounts of PV waste for their operations. Additionally, the interviewee suggested that "*there are no big competitors who are involved in PV recycling in Germany.*

Our biggest competitor is illegal exports of PV waste; if it was forbidden, we would have many more modules to recycle or stay in the market as reuse. It would be easier to invest in new recycling technologies if PV waste is sufficient. There are no figures on how many PV modules waste is exported". Regarding the reasons why there is no data on the export of PV module waste, the interviewee stated: "*you do not need a license if you want to trade PV waste. It is easy for them to distribute PV waste to other countries*". Interviewee L concluded that "*similar to other e-waste, it is happening now for PV modules*". The interviewee meant that PV module waste is a target of e-waste treatment, where the goal is to find the cheapest way to dispose of it without considering recyclability or reusability.

The reuse content refers to several materials or components that are reused without considering recycled content. It is hardly possible within the EU PV supply chain as it is not possible to dismantle components without breaking them. Especially since the new PV modules have higher requirements/different dimensions, making reuse content a difficult objective. Recycled content is something that the EU PV supply chain would benefit from since it has a direct impact on the PV module's CO_2 value. However, as noted by the experts, it is difficult to increase it as there is simply not enough PV waste to generate secondary materials. Furthermore, the findings reveal that the day when there will be a sufficient amount of PV waste for secondary materials will not come fast, as the waste is directed outside the EU, resulting in the unavailability of processing the waste within the EU to generate secondary materials cullets.

The results show that the lifetime of the PV modules could be improved if the PV modules had information traceability. For example, reasons for PV module failures could be analysed by PV module or components producers to improve the quality of their products. Expected reuse has one of the most promising impacts on the EU PV supply chain. Around 50% of the PV modules could theoretically be reused after their first life. However, the difficulty is that PV modules are collected differently across the EU member states, especially for the residential segment, which often results in PV modules being already broken due to dismantling and transportation processes. The experts demonstrated that constraints are heavily impacting the recyclability of the PV modules. Since the PV module is encapsulated, it is not a simple procedure to recycle it. The findings show that recyclers have limited capability to recover high-value materials without cooperation from the rest of the supply chain. The cooperation could be from allowing the recycler to access the product material composition or making PV modules more easily identifiable based on their characteristic for sorting processes that would allow diverting PV modules to recycling based on compatibility of PV modules' technological design versus various recycling processes.

The results of the inputs collection demonstrate that the EU PV supply chain organisations express above medium interest in solving those constraints and that the organisations are feeling the impact of those constraints on their operations. It reveals that there is a motivation from the organisations to overcome the constraints; however, as mentioned by the experts, there is limited power they can express as the EU PV supply chain is heavily reliant on the supply chain outside the EU, which is mainly present in China.

3.5. Application of the decision-making method for evaluating circularity constraints of the European Union's photovoltaics circular supply chain

With the (1) identified circularity-related constraints of the EU PV circular supply chain, (2) results of input collection from experts of EU PV organisations, and (3) expert weighting of criteria, the TOPSIS method can be used. The principle of TOPSIS is to have a matrix of alternatives and criteria to find the distance to the ideal solution while considering the distance to the worst solution. Table 3.14 shows the weighted decision matrix.

Table 3.14. TOPSIS weighted decision-making matrix

Weighted decision matrix	**Reuse content**	**Recycled content**	**Lifetime**	**Expected Reuse**	**Recycling**	**Impact**	**Interest**
Unpredictable volumes for reuse and recycling	0.25	0.46	0.36	0.79	0.78	0.26	0.22
Insufficient value chain collaboration	0.19	0.39	0.42	0.50	0.65	0.17	0.18
Uncoordinated legislation in Europe	0.24	0.40	0.42	0.75	0.73	0.28	0.19
Insufficient purity of recyclates for reinsertion in PV product	0.18	0.47	0.39	0.39	0.89	0.27	0.25
Hesitant exchange of information	0.28	0.50	0.64	0.75	0.87	0.28	0.25
Insufficient traceability of PV modules	0.25	0.34	0.72	0.81	0.71	0.28	0.23
Immature recycling methods often result in downcycling	0.17	0.38	0.26	0.31	0.92	0.25	0.22

End of Table 3.14

Weighted decision matrix	**Reuse content**	**Recycled content**	**Lifetime**	**Expected Reuse**	**Recycling**	**Impact**	**Interest**
Illegal end-of-life PV module exports to non-European countries	0.29	0.50	0.45	0.75	0.72	0.30	0.25
Poor logistics handling in the reverse supply chain	0.27	0.38	0.61	0.79	0.62	0.27	0.18
Conventional PV recycling is hardly profitable	0.18	0.47	0.40	0.46	0.89	0.25	0.13

The most critical constraint is illegal end-of-life PV module exports to non-European countries. It affects reuse content and recycled content and impacts organisations and their interest in solving the constraint. Unpredictable volumes for reuse and recycling are a critical constraint for improving the expected reuse of PV modules. Hesitant exchange of information has the highest value for the lifetime indicator. Lastly, immature recycling methods often result in downcycling. The constraint has a very high score, e.g., 0.974 out of 1, for the recycling indicator. Table 3.15 shows the final calculations based on the TOPSIS method. The performance ratio represents the shortest distance to the ideal scenario (which equals 1).

Table 3.15. Ranking of the constraints from highest to lowest performance ratio

Constraints	**Performance ratio**	**Ranking**
Hesitant exchange of information	0.974	1
Insufficient traceability of PV modules	0.867	2
Poor logistics handling in the reverse supply chain	0.747	3
Illegal end-of-life PV module exports to non-European countries	0.731	4
Unpredictable volumes for reuse and recycling	0.661	5
Uncoordinated Legislation in Europe	0.627	6
Conventional PV recycling is hardly profitable	0.364	7
Insufficient purity of recyclates for reinsertion in PV product	0.326	8
Immature recycling methods often result in downcycling	0.184	9
Insufficient value chain collaboration	0.182	10

The hesitant exchange of information is closest to the ideal scenario compared to the other alternatives. The insufficient value chain collaboration is furthest away from the ideal scenario.

Table 3.16 shows the change in TOPSIS results with each additional organisation input. A minimum of five organisation inputs are required, as each CSC stage should be represented. After the sixth organisation's input, the TOPSIS result does not change for the first ranking alternative, "hesitant exchange of information".

Table 3.16. Change in the TOPSIS ranking based on each additional organisation input

	5 org. (from each CSC stage)	**6 org.**	**7 org.**	**8 org.**	**9 org.**	**10 org.**	**11 org.**
Unpredictable volumes for reuse and recycling	4	4	5	5	5	5	**5**
Insufficient value chain collaboration	9	9	7	6	6	9	**10**
Uncoordinated Legislation in Europe	3	2	3	4	4	4	**6**
Insufficient purity of recyclates for reinsertion in PV product	10	7	8	9	9	7	**8**
Hesitant exchange of information	2	1	1	1	1	1	**1**
Insufficient traceability of PV modules	7	10	9	7	7	3	**2**
Immature recycling methods often result in downcycling	8	9	10	10	10	10	**9**
Illegal end-of-life PV module exports to non-European countries	1	3	2	2	2	2	**4**
Poor logistics handling in the reverse supply chain	6	5	4	3	3	6	**3**
Conventional PV recycling is hardly profitable	5	6	6	8	8	8	7

To investigate further whether there is sufficient input from the organisation and whether TOPSIS results are consistent, the Kendal W coefficient is used. The coefficient is 0.809, which means there are a low number of ranking changes when considering five to 11 organisations' inputs (seven outcomes of TOPSIS results). Table 3.16 shows the difference in the ranking of constraints based on coding and the TOPSIS method.

Based on Figure 3.4, the hesitant exchange of information also affects traceability, poor viability of circular business models and insufficient value chain collaboration (Nyffenegger, et al., 2024). The figure demonstrates how each of the identified constraints is linked with the enabler and with the company's circular economy-related goals. Potential enablers for the hesitant exchange of information are increased access to information on PV modules, taking responsibility at EoL, engaging in EU PV industry standards and regulations, etc. Thus, the potential solutions to address the hesitant exchange of information relate to policy instruments and data exchange with traceability technologies.

Researchers have evaluated what would be the potential costs of introducing technology to store information and allow traceability of the PV modules (Radavičius et al., 2021). A near-field-communication (NFC) tag that costs ~0.30 EUR/piece can be in-laminated within the PV module. The integration of the NFC system in the production line would cost around EUR 20,000 per 200 MW PV module production line.

As regards policy instruments, as interviewees and experts mentioned, there is a lack of involvement from PV industry organisations. EU countries adopt directives differently in each EU country. Considering that over 90% of PV modules are manufactured outside the EU, there is a need for higher involvement to develop and improve policies to ensure circularity in the EU PV industry. With a lack of domestic production, reuse, recycling, and longevity should be ensured to the maximum point. At the moment, there is a lack of progress in ensuring that imported PV modules meet the needs of circular strategies, from information sharing to preventing EoL PV module exports from EU countries.

The second most relevant CE constraint is the insufficient traceability of PV modules. This results in poor logistic handling in reverse supply chain and unpredictable volumes for reuse and recycling. The least relevant constraints are immature recycling methods that often result in downcycling, insufficient value chain collaboration, and insufficient purity of recyclates for reinsertion in PV production. With the lack of waste, it is not possible to scale up various recycling approaches that could improve recyclability over time to avoid downcycling. It is difficult to implement standards related to PV modules and the characteristics of their components, such as size or dimensions, due to rapidly changing technology. The highly competitive PV industry is not yet actively looking at recycled materials for insertion in PV components due to lack of it and potentially higher prices.

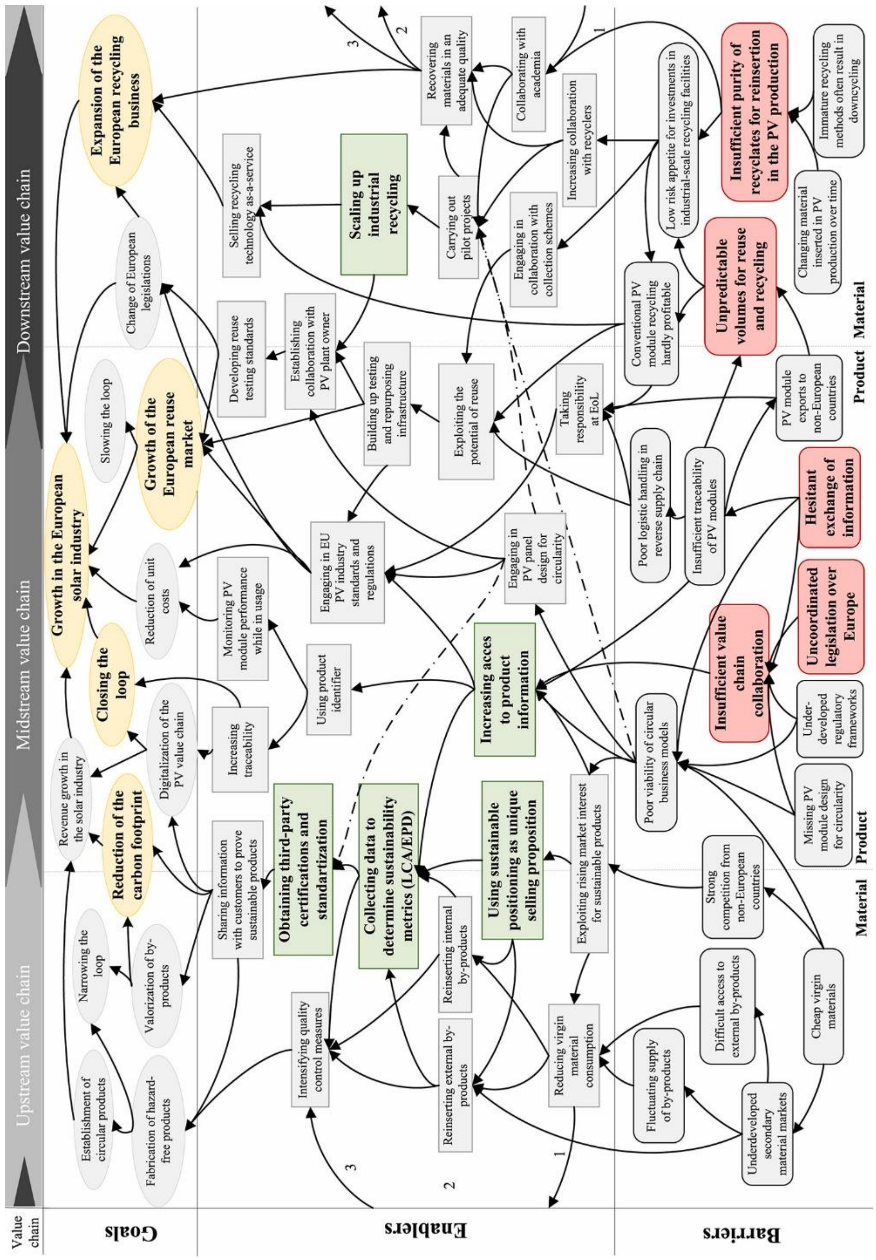

Fig. 3.4. Map of EU PV circular economy barriers, enablers, and goals (source: Nyffenegger et al., 2024)

Table 3.17 compares ranking constraints based on the constraints mentioned in the interviews versus TOPSIS results. The table shows that prioritising constraints only based on the number of times the constraints are mentioned by interviewees is not sufficient. By applying the TOPSIS method, which incorporates criteria weighting and inputs from EU PV organisations, different ranking is established.

Table 3.17. Comparison of ranking of constraints based on code texting versus TOPSIS application

CE Constraints categories	**Ranking based on the total number of codes**	**Ranking based on TOPSIS results**
1. Unpredictable volumes for reuse and recycling	11 (1)	5
2. Insufficient value chain collaboration	8 (2)	10
3. Insufficient purity of recyclates for reinsertion in PV production	7 (3–4)	8
4. Uncoordinated legislation in Europe	7 (3–4)	6
5. Hesitant exchange of information	6 (5–10)	1
6. Insufficient traceability of PV modules	6 (5–10)	2
7. Immature recycling methods often result in downcycling	6 (5–10)	9
8. Illegal PV module exports	6 (5–10)	4
9. Poor logistics handling in the reverse supply chain	6 (5–10)	3
10. Conventional PV recycling is not profitable yet	6 (5–10)	7

Overall, the results show that the hesitant exchange of information has the highest ranking. The hesitant exchange of information is linked with other constraints, mainly insufficient value chain collaboration, poor viability of circular business models, insufficient traceability of PV modules and poor logistics handling in the reverse supply chain. The identified possible enablers are, for example, taking responsibility at EoL, exploiting the potential of reuse, increasing access to product information or using a product identifier. The findings show that even though the top circularity constraint was identified, it should be addressed by also considering other constraints as they are linked with each other. The identified solutions for the EU PV supply chain can be used to solve the most relevant constraint. However, it should also be noted that when the constraints are interconnected, the selection of possible solutions should also be based on whether it would affect only the identified top-ranked constraint or would also help to overcome other high-ranked constraints as well, especially if those constraints are linked.

3.5.1. Theoretical discussion

The study by Franco and Groesser (2021) identified similar PV industry circularity barriers relative to this dissertation's results (barriers are referred to as constraints in this dissertation). The only missing barrier in their study was illegal PV module exports, which this study identified as the fourth most relevant barrier to solve. Mathur et al. (2020) identified two out of ten PV industry circularity barriers analysed in this study. Tsanakas et al. (2020) also identified two out of 10 barriers in their study (same ones as Mathur et al., 2020). In the case of Rabaia et al. (2022), their study had five out of ten barriers that match this study's barriers. In all these cases, the researchers did not analyse the barriers to identify their significance. This study's results advance the assessment of EU PV circularity barriers by comprehensively analysing how the barriers affect the EU PV circularity. The results allow for the prioritisation of barriers by their impact on the EU PV circularity potential.

The CSC model proposed by Iacovidou et al. (2020) looks at the wider system, resource recovery system, and the processes of production, consumption and management. It tackles the aspects of the legislative landscape, behaviours of the actors, technology and motivation of businesses and the market to transition to CE. While the model explicitly aims to understand the system's challenges in solving the constraint, it does not provide guidance on how to detect or analyse those challenges. The model provided in the dissertation fills the gap by proposing the system of CSC organisations to work together in determining constraints and their effect on the system. Additionally, the aim is to prioritise the constraints to solve the one that has the biggest impact. Iacovidou (2020) also suggested that further research is needed to assess and evaluate the challenges, which is exactly what this dissertation is focused on by proposing a model and tool to identify and assess the challenges that are referred to as circularity constraints.

Another approach to conceptualising CSC is proposed by Awan (2021). The author focused on how the policies, user behaviour, market activities, etc., are linked to the CSC stakeholders in terms of their strategies and expectations towards CE. The research findings conclude that there is a high amount of linkage between the CSC stakeholders and that cooperation should be based on positive impact for more than one stakeholder. Specifically, the authors conclude that organisations need to be included in decision-making when tackling circularity issues so that these organisations can identify where and how they fit in the CSC model. The model proposed in this dissertation focuses on filling the gap of how to include the CSC organisations in making changes to CSC for improved circularity. It is achieved by integrating feedback from CSC organisations in determining and evaluating CSC circularity constraints by considering circularity constraints' impacts on each organisation.

In this research, the evaluation of circularity barriers, referred to as constraints, was conducted using a three-step approach: (1) a list of indicators, (2) the Delphi method to assign weights to the indicators, and (3) the TOPSIS method to rank the constraints. The evaluation also required inputs from the PV organisations in terms of how they see circularity constraints affecting indicators. The inputs were provided from 1 (low impact) to 5 (high impact) by 11 PV organisations from different circular supply chain stages. This method of collecting input relies heavily on the perceptions of organisations and their representatives regarding constraints. These perceptions are significantly influenced by the CSC stage they are in and their experience. To address this limitation, interviewees' comments were collected to understand the reasoning behind their inputs. This step provided insights into the background of their perspectives on EU PV CSC circularity constraints. By considering these comments, readers and researchers can assess whether the interviewees comprehended the task of providing inputs by evaluating how constraints affect circularity.

To ensure enough organisations were interviewed for input collection, it is important to demonstrate consistency of ranking with each additional interviewee's input. Table 3.16 shows that after six interviewees' input, there was no change in the first rank of circularity constraint. The second, third and further ranks changed with each additional interviewee's input. Thus, the results demonstrate that the consensus on the highest circularity issue by the industry is agreed only for the first circularity constraint.

To ensure there are no significant fluctuations in the rankings, the Kendall W coefficient was used. TOPSIS ranking results were generated starting from the input provided by five organisations (representing five CSC stages) and included additional inputs incrementally from six to 11 organisations, resulting in seven different rankings of circularity constraints. The Kendall W coefficient indicated a high agreement, with a value of 0.809, demonstrating no significant fluctuations in the rankings from the input provided by 11 organisations. Given the five CSC stages and the limited number of EU PV organisations (except for the usage stage), obtaining a higher number of interviews was challenging. Future research in an industry with a larger number of organisation inputs from CSC stages could potentially yield more consistent testing results.

Compared to Mhatre et al. (2023) and Gedam et al. (2021) studies of prioritising circularity barriers, this study differs in terms of unique indicator systems and ensuring that the barriers (referred to as constraints in this study) are not standalone obstacles in an industry. The constraints that were identified from the previous research by Nyffenegger et al. (2024) consisted of semi-structured interviews with EU PV organisations. The text coding ensured that the circularity constraints reflect at least two circular supply chain stage actors, such as a product manufacturer and recycler.

The limitation of this study is a rather small number of interviewed representatives of EU PV organisations, especially from the "usage" stage of the circular supply chain, which contains a substantial number of PV organisations dealing with PV systems' installation or distribution. An additional limitation is the number of constraints that were assessed. Beyond ten constraints could be assessed if a different input collection method (structured interviews) would have been used. The current method limited constraints to ten as a higher number would have prolonged interviews beyond one hour, which would have created a risk of finding interviewees due to the extensive time requested.

The application of constraints within the context of circular supply chains allowed the identification of circularity constraints at the circular supply chain level. The theory of constraints in this study was adapted in the context of a circular supply chain instead of the mainstream context of manufacturing. The measurement unit to determine a constraint in this study was the proposed indicators instead of productivity-related indicators in a manufacturing context. This study broadened the application of the theory of constraint within the circular economy field, specifically for identifying circularity constraints within circular supply chains. Further research could use the proposed constraints identification, indicator system, indicators weighting method and inputs collection method for other industries.

3.5.2. Practical discussion

The top-ranked circularity constraint is the hesitant exchange of information. This constraint encompasses a lack of available information, such as PV module material composition, traceability data, reasons for PV module failures, and data on end-of-life PV waste management (collection, reuse, export for second-hand applications, etc.). The industry shows low incentives to address this issue independently as the upstream supply chain is located outside the EU, and the downstream supply chain is not regulated to manage this information. Additionally, there is very little pressure from the industry itself to implement these solutions. The pressure is little due to the small number of recyclers or reuse organisations. These companies are currently very small and do not have the resources to participate in policy recommendations. Thus, the industry is slow to develop these solutions. It will be inevitable that these solutions will be made when there will be significant waste in the EU. However, the longer the delay in ensuring the disclosure of materials in new PV modules, the longer the EU will accumulate PV modules without proper information on them. To address this issue, three interconnected solutions are proposed:

- **Product circularity datasheet:** PV manufacturers should be obligated to disclose data on material content. This data should include component material content above a 0.1% weight-to-weight ratio and specific materials of concern, such as silver content and hazardous materials (phosphorus, fluorine, lead, and cadmium). Disclosure of this data would allow EoL organisations to manage their activities more efficiently.
- **Regulating EoL organisations on data collection**: Each EU state currently regulates different operations of waste collectors and organisations dealing with PV module repair/reuse with their internal databases. A minimum requirement could be proposed for these organisations, such as to collect data on PV module failure reasons and send it to PV module producers. This solution would enable feedback collection at the downstream supply chain about PV module failures, which could then be used by the upstream supply chain to improve their PV products. Additionally, recyclers would have higher precision in forecasting waste streams.
- **Establishing an EU-wide database on PV circularity data**: Each PV waste collector currently maintains its database of PV modules entering the market and pays an extended producer responsibility fee. Centralising these databases and including traceability requirements (minimally by barcodes for each PV module) with other data from EoL organisations would improve the effectiveness and efficiency of EoL processes. This would also enhance the longevity of PV modules, as data could be sent to original PV module producers, allowing them to learn from PV module failure data (e.g., encapsulation material issues and junction box failures).

The digital passport regulation for PV modules is expected to come into force by 2025–2026. This study highlights the importance of its application to its full extent, to include all types of materials within the materials passport. From the main author's experience, who has partaken in a working group providing recommendations on the digital passport for PV modules, some propositions mention only specific materials, such as toxic materials or critical raw materials. For high-value recycling, it is essential to list all of the materials. The current policy of the digital passport regulation does not solve the data accessibility issue. It is not enough that each organisation has a materials passport document somewhere stored on its website. For fluent data access and automatisation, a database is essential to host and manage the information regarding digital passports of PV modules.

Additionally, the European Commission has initiated a review of the directive for waste from electrical and electronics equipment (WEEE) due to the difficulty of implementing it by extended-producer-responsibility organisations. The results of this study suggest that EPR organisations' databases should be centralised to ensure the implementation of WEEE directive objectives, such as reuse, repair, and recycle. This study also suggests that by integrating data on waste collectors, reuse organisations, etc., the database would work more effectively. This solution would also allow for the tracing back of the PV waste that is exported outside the EU, which is often illegal. At the moment, none of the known drafted EU policies aim to solve the issue of PV exports outside the EU.

Three policy actions are proposed for policymakers. They aim to improve circularity in the EU PV circular supply chain. As this research demonstrates the essential factor of the information exchange constraint, the first step for the successful design and implementation of the policies is gathering feedback from EU PV organisations in terms of what types of information are relevant to be stored in the database or the PV circularity datasheet and how it should be handled, stored, accessed, etc. The PV industry organisations can start to disclose their details on the best suitable recycling processes for their PV modules or list materials present in the PV module. This step should allow higher circularity in the long term, as due to the wide variety of PV modules, the whole industry should standardise the practices of information sharing. At the moment, voluntary-based databases for disclosure product materials, such as Sweden-based Sundahus, can be used to store PV module-related data in third-party databases.

3.5.3. Application analysis of the theoretical framework model for the circular supply chain

The proposed theoretical framework model to improve CSC performance was based on analysed theories. The most evident theories were the constraints, knowledge management, resource-based view and resource-dependency theories. Three questions were formulated to analyse the supply chain circularity, based on which the tool and research methods were proposed for identifying and assessing circularity constraints:

1. Which knowledge is required for circular purposes, and how can it be acquired or created?

2. What current resources do organisations possess for circularity purposes, and what limitations do organisations have to achieve higher levels of circularity?

3. What are the constraints for achieving CE strategies within CSC?

The theory of constraints was used to identify the constraints limiting the growth of CE in the supply chain. The theory was used to answer the following question (Table 1.5): "*What are the constraints for achieving CE strategies within CSC?*" To answer the question, a total of 20 constraints were identified, with 10 of them analysed in further research by gathering inputs from organisation experts. For example, the silicon material producer does not handle waste properly, leading to difficulties in its treatment by the recycler. The company goals within CE were also analysed to reflect on CE strategies that organisations aim for. Table 3.3 lists the goals, with 12 out of 20 experts indicating that "closing the loop" is a more relevant CE strategy. The other most mentioned strategies were related to the reduction of carbon footprint and expansion of the European recycling business.

The knowledge management theory was incorporated into the proposed model to answer the following question: "*Which knowledge is required for circularity purposes, and how can it be acquired or created?"* The model also incorporates the following statements for assessing CSC: (1) *what knowledge is required to develop circular processes*, (2) *how the knowledge should be integrated within the organisation's process*. The required knowledge within a CSC is reflected through the identified hesitant exchange of information constraint, which was also ranked as the Top 1 constraint limiting circularity within the EU PV supply chain. Based on semi-structured interviews with the experts, the knowledge related to (1) environmental product declarations of LCA, (2) information on materials content, (3) information on waste, and (4) data on PV module failure reasons. An analysis of how it can be acquired was made using enablers, mainly the "implement internal and third-party certification/standardisation", "increase access to product information", and "collect data to assess sustainability metrics (LCA/EPD)". The experts face issues in developing circular processes, e.g., high-value recycling, without having access to product history. The analysis of "*how the knowledge should be integrated within the organisation's process"* was achieved by synthesis of the experts' inputs to develop recommendations in handling the EU PV end-of-life operators' data through a centralised database and establishing product circularity datasheets.

The analysed resource-based view and resource-dependency theories were employed to formulate the following question: "*What current resources do organisations possess for circularity purposes, and what limitations do organisations have to achieve higher levels of circularity?*" The question is answered through the statement analysis indicated in the model: (1) *access to circular materials, components and products*, (2) *access to a sufficient amount of end-of-life products and their data for high-value recycling and other EoL processes*, (3) *to design circular materials, components, and products*, and (4) *to develop and maintain circular processes*. These statements were analysed through semi-structured interviews with the EU PV organisation experts. The current resources required for circular processes for EU PV supply chain organisations were identified through organisations' goals, as they already implement CE principles to some degree. The following resources were identified: (1) high-value recycling equipment, (2) infrastructure for PV modules reuse, and (3) recyclable plastics. The limitations to utilise the resources were found to be a lack of constant supply of EoL PV waste, fragmented regulation across EU countries and the lack of incentives for a circular PV module design. The access to circular MCPs was analysed through constraints, mainly the "fluctuating supply of byproducts" and "insufficient purity of recyclates for reinsertion in PV production". Access to a sufficient amount of EoL products and their data was analysed by exploring the constraints of "unpredictable volumes for reuse and recycling" and "hesitant exchange of information". The organisations' capabilities to design circular MCPs were analysed through the constraints. Those capabilities are limited due to the low amount of high-value secondary materials used in the products. Additionally, the recyclability or PV module design is limited due to a lack of feedback from the downstream supply chain, i.e., design features required to make products more efficient in the recycling process. Organisations' capabilities to develop and maintain circular processes, mainly the closed-loop supply chain and growth of PV module reuse processes, are currently limited. One of the key limitations is the illegal export of PV modules to non-EU countries. Due to this, the recyclers are not getting sufficient amounts of PV modules, which prohibits them from investing in high-value recycling processes. Even though some of the recyclers have the equipment, the EoL product flow is poorly managed, resulting in an inability to produce secondary materials by the recyclers.

The findings reveal that the application of the theoretical model allows for the identification of concrete constraints within the supply chain. The most relevant constraint was identified as the hesitant exchange of information. The results also include potential enablers to overcome the constraints, as seen in Table 3.2. The limitation of the theoretical framework model is that it does not explore how the constraints are dependent on each other. As discussed, the hesitant exchange of information is heavily linked with other constraints, such as insufficient traceability of PV modules. Even though possible enablers are proposed, e.g., increased access to product information, it is not clear whether implementing it will address the hesitant exchange of information constraint and other linked constraints to it. A further analysis of the enablers is required to determine if they would sufficiently address the constraints to increase circularity within the supply chain.

The assessment of the EU PV circular supply chain was done according to a proposed theoretical framework, which was based on knowledge management theory, resource-based view theory, resource-dependency theory and theory of constraints to assess supply chain circularity. The theory of constraint relevance is unlikely to change, as all types of systems have some constraints limiting their performance. The knowledge management theory is evolving due to new capabilities for the rapid exchange of information and intellectual property of organisations. With a higher throughput of information across organisations, the relevance of knowledge management may diminish in future supply chains as it becomes less difficult to acquire relevant information with rapidly evolving information technologies. The resource-based view suggests that an organisation should utilise its strengths in competition. With increasing interdependence across the supply chain actors, especially in the circular supply chain, as the dissertation's results show, one organisation can improve circularity only to a limited degree without cooperating. While the theory allows for the determination of the bottleneck of circularity performance when cooperation is not in the equation, it is becoming less critical. Organisations are becoming more aware of an impossible significant improvement in circularity when working single-handedly, using their resources alone. The resource-dependency theory suggests that it is essential to cooperate to access relevant resources for the organisation. The theory will likely increase in relevance as evidenced by the dissertation's results; the supply chain actors must pool their knowledge and resources in a coordinated manner to, for example, ensure closed-loop circular economy strategies.

The influence on CSC actors comes from regulatory factors, networks, and stakeholders. The un-even approach of regulatory factors was identified, e.g., disclosing specific data or different approaches to enforce EoL management for the product manufacturer. The inability of the supply chain to improve the quality of the recyclates results in their flow to other industries. While the recyclers could potentially improve recycling processes, they are not receiving sufficient amounts of waste. This is because one of the main stakeholders influencing the performance of CSC organisations that buy and resell the EoL PV modules. They are responsible for the leakage of PV waste outside the EU, which could otherwise be processed by the recyclers or reuse organisations.

A tool for identification and assessment of the constraints was proposed with a list of indicators and sequence of the following steps: (1) semi-structured interviews with CSC actors, (2) transcripts text-coding to identify CE constraints, enablers and goals, (3) weighing nine indicators by CSC experts, (4) collection of inputs from CSC actors, and (5) the TOPSIS application to identify most relevant CSC CE constraint. The use of semi-structured interviews in combination with text coding allowed for the identification of circularity constraints. The research results indicate that there was a sufficient amount of semi-structured interviews made with the experts as after the 7th interview, the number of unique constraints identified decreased significantly (Fig. 2.2). The evaluation of those constraints on organisations' CE performance was achieved through the Delphi method, collecting inputs from 12 experts of EU PV supply chain organisations and employing the TOPSIS method. The Delphi method, composed of six experts, was used to provide weights for the proposed indicators to measure circularity. While two indicators were irrelevant to consider, as stated by the experts, it was due to EU PV supply chain specifics that use no biomass-based products. Two rounds were sufficient to achieve a high consensus between the experts. The collected input from experts of EU PV organisations regarding their perception of how constraints affect the indicators were analysed by conducting TOPSIS decision-making. It was sufficient to use input from at least six experts to achieve a stable position of the Top 1 constraint, which was the "hesitant exchange of information" (Table 3.16). Also, minor ranking changes were found for the rest of the constraints when adding subsequent expert data, from 6 to 11, as it resulted in the Kendel W coefficient of 0.8.

The dissertation's goal was to propose a theoretical model of a circular supply chain. The proposed model includes an assessment of the circular supply chain to improve the CSC performance. The theoretical framework was applied to the EU PV supply chain to identify and assess constraints via the proposed tool. The results revealed that the proposed tool is suitable for determining specific CSC constraints and allows for the analysis of the impact constraints have on organisations' CE performance to rank the constraints. The dissertation also suggested practical recommendations based on which cooperation can be achieved, and the constraints can be solved.

3.6. Conclusions of the Third Chapter

1. The PV industry consumes a lot of resources, such as aluminium, glass, silver, copper, and silicon. There is little upstream supply chain presence in the EU; over 90% of the components are manufactured in Asia, mainly China. Three main challenges for the EU PV circular supply chain are: (1) production of components that are required to generate renewable energy is concentrated outside the EU, (2) high material consumption, especially for silver and copper, and (3) underdeveloped end-of-life processes. Thus, the industry is highly important in terms of circularity benefits to reduce dependency on raw materials.
2. After semi-structured interviews and text coding using the MAXQDA program, CE constraints, enablers, and goals were identified. Based on the number of codes from the interview transcripts, rankings were made for the code categories. The Top 3 constraints were: (1) unpredictable volumes for reuse and recycling, (2) insufficient value chain collaboration, and (3) insufficient purity of recyclates for reinsertion in PV production. The Top 3 potential enablers to address constraints were: (1) implementing internal and third-party certifications/standardisation, (2) scaling up industrial recycling, and (3) increasing access to product information.

The Top 3 goals of EU PV organisations in terms of circularity were: (1) closing the loop, (2) reduction of carbon footprint, and (3) expansion of the European recycling business. The results demonstrate a variety of circularity issues within the industry and potential solutions to address them.

3. Two Delphi rounds were conducted to determine weights for the indicators. Six experts ranked nine criteria. After the first round, two indicators were eliminated, e.g., biomass content and outflow recirculation in the biological cycle. These two indicators were irrelevant for the PV industry due to the presence of wood or similar renewable content. The first round resulted in a W coefficient of 0.30 (out of 1). The closer it is to 0, the less agreement is between the experts on which indicators are more relevant than others. The second round concluded with a W coefficient of 0.72, which demonstrates a strong agreement between the experts.
4. Twelve EU PV organisation representatives were interviewed in a structured way to determine their perceptions of the constraints on indicators, from 1 (low impact) to 5 (high impact). PV organisations see that indicators, such as reuse content, are hardly possible in the PV industry due to changing technologies and components. Considering the 25–30-year lifetime of PV modules, it is difficult to use secondary components in new PV modules. However, interviewees agree that it is important to know data on PV modules, such as what is it made of, to allow circularity processes.
5. The application of TOPSIS to determine which constraint is most relevant resulted in the hesitant exchange of information being ranked first. The constraint is related to other issues, such as the lack of traceability on PV modules. The solution for the top one constraint relies on policy instruments and data storage with exchange solutions for the industry to implement. With the hesitant exchange of information receiving 0.974 out of 1 performance ratio, it demonstrated that there is an almost full consensus of which constraint needs to be prioritised.

General conclusions

1. The literature review revealed a complex system of circular supply chains. Multiple stakeholders are required to ensure circularity in any industry. The impact of circular supply chain actors accumulates throughout the circular supply chain, resulting in limited options for the downstream supply chain to improve circularity. By integrating knowledge from all steps of the circular supply chain, a broad view of circularity issues and potential solutions can be analysed and proposed.
2. The dissertation expands the application of the theory of constraints by applying it to the CSC system. Furthermore, the resource-dependency and resource-based view theories are analysed to identify capabilities and resources that the CSC requires to improve circularity. The knowledge management theory was analysed to investigate the required information and how it should be managed by CSC.
3. Based on the literature review and ISO 59020 standard, the main circular economy indicators were used to measure circularity constraints. Those indicators, such as recycled content or reuse content, are universal indicators applicable to most industries. Two additional constraints were included based on cooperation theory and resource-based view: the impact of constraint on organisation circularity potential and organisation interest in solving the constraint. The combination of the indicators within one

system results in the capability to measure various types of constraints that might be diverse depending on the selected industry.

4. The theory of constraints, resource-based view theory, resource-dependency theory, and knowledge management theory were integrated into the theoretical framework model of a circular supply chain. The proposed theoretical framework model aims to improve CSC circularity by assessing CSC circularity constraints and equally involving all of the organisations in the assessment process. The first two steps, the identification and assessment of constraints, are the focus of the dissertation.
5. The proposed tool consists of an indicator system to measure CSC circularity and steps to assess circularity constraints. The application of the tool revealed a list of 20 EU PV industry constraints that limit the industry's circularity. The constraints are diverse, from cooperation to technological challenges. Nineteen constraints were mentioned by at least two different supply chain stage representatives, meaning almost all of the constraints cannot be solved by organisations single-handedly.
6. The TOPSIS method application resulted in the selection of the most impactful constraint: the hesitant exchange of information. With most of the production within the PV industry happening in Asia, information access is limited. A policy approach of the European Commission, EcoDesign, digital product passports or Net-Zer-Industry-Act, can be utilised to solve the constraint. Otherwise, as the results show, the EU PV industry will not overcome the constraint as it has limited power to influence Asia's PV supply chain.
7. The dissertation results allowed for the identification of potential enablers, which can serve as a further step in the establishment of cooperation and the solving of constraints. Compared to other research on identifying and analysing PV industry circularity issues, this study involves different actors of the EU's PV CSC equally by connecting their insights (constraints, barriers, and enablers) to identify the most relevant CE constraint.

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Summary in Lithuanian

Įvadas

Problemos formulavimas

Pasaulio ekonomika susiduria su būtinybe pereiti prie žiedinės ekonomikos. Išteklių trūkumo ir būtinybės užtikrinti šalių ir regionų atsparumą klimato kaitos kontekste lemia organizacijų veiklos pokyčius. Vienas iš pokyčių, ypač svarbus verslo įmonėms, susijęs su organizacijos funkcijų valdymu, bendradarbiavimu su tiekėjais ir kitais suinteresuotaisiais subjektais. Siekiant užtikrinti, kad įvairios organizacijos ŽE ekosistemoje turėtų atitinkamas procedūras ir procesus, reikalingi aiškūs metodai, kaip tai įgyvendinti.

Organizacijos noriai tyrinėja ŽE esančias galimybes, siekdamos padidinti savo verslo konkurencingumą, rasti naujas rinkas, verslo modelius ir pan. Tačiau galimybes įgyvendinti ir tobulinti žiedinius procesus paprastai riboja organizacijų turimi ištekliai. Tai lemia, kad dėmesys sutelkiamas į susiaurintas strategijas, pavyzdžiui, toksiškų medžiagų pakeitimu netoksiškomis medžiagomis, medžiagų suvartojimo mažinimą ir pan.

Kalbant apie ciklo uždarymo arba sulėtinimo strategijas, vienas veiksmas grandinėje, vykdomas nebendradarbiaujant su kitais ekosistemos dalyviais, gali lemti ribotą ŽE taikymą. Organizacijoms neišvengiamai reikia bendradarbiauti su savo tiekimo grandine, kuriant žiedinius procesus, siekiant pagerinti medžiagų, komponentų ir gaminių pakartotinį naudojimą, perdirbimą ir remontą. Pagrindinis vyraujantis požiūris – produktų gamintojai turi vadovauti žiedinių procesų plėtojimo iniciatyvai. Dėl šio požiūrio daugiausia dėmesio skiriama gamintojų žiediškumui gerinti, kas lemia nebūtinai visos tiekimo grandinės žiediškumą. Taigi, iškyla problema, kad organizacijoms reikia metodų, kaip dirbti savo tiekimo grandinėje, kad kartu su kitomis ekosistemos dalimis palaipsniui pagerintų žiediškumą.

Darbo aktualumas

Saulės fotovoltikos tiekimo grandinėje, kurioje dauguma komponentų gaminami ne Europoje, žiediškumo poreikis yra labai svarbus. Kyla iššūkių, kaip sistemingai valdyti tiekimo grandinės organizacijas, kad būtų pagerintas visos tiekimo grandinės žiediškumas. Disertacijoje pateikiamas teorinis žiedinės tiekimo grandinės modelis, skirtas tiekimo grandinės žiediškumui didinti. Taip pat pateikiamas įrankis tiekimo grandinės žiediškumo apribojimams nustatyti ir įvertinti. Europos Sąjungos (toliau – ES) saulės fotovoltikos tiekimo grandinės žiediškumo svarba išauga dėl Europos Komisijos (toliau – EK) pasiūlyto reguliavimo mechanizmo, kuriuo siekiama remti „Net-Zero“ technologijas, įskaitant saulės fotovoltiką. Tikimasi, kad iki 2030 m. ES saulės fotovoltikos pramonės gamybos apimtys padidės nuo vos 6 GW fotovoltinių modulių gamybos iki 30 GW – nuo silicio gamybos iki galutinių fotovoltinio modulių gaminimo. Pramonės augimą remia paskatos, numatytos „Net-Zero Industry Act“. Jos taip pat susijusios su žiedine ekonomika, pavyzdžiui, išmetamo CO_2 kiekio mažinimu. Žiedinės ekonomikos apribojimų įvertinimas leidžia ES saulės fotovoltikos tiekimo grandinei didinti savo gamybą ES, atsižvelgiant į ŽE apribojimus, su kuriais susiduria tiekimo grandinė.

Tyrimų objektas

Darbo tyrimo objektas – žiedinių apribojimų vertinimas Europos Sąjungos fotovoltikos tiekimo grandinėje.

Darbo tikslas

Darbo tikslas – sukurti teorinį tiekimo grandinės žiediškumo vertinimo modelį, kurio paskirtis yra padidinti žiediškumą pasirinktoje tiekimo grandinėje.

Darbo uždaviniai

Darbo tikslui pasiekti sprendžiami šie uždaviniai:

1. Išanalizuoti literatūrą apie žiedinės ekonomikos principus tiekimo grandinėje.
2. Išanalizuoti teorijas ir sampratas, padedančias nagrinėti žiediškumo apribojimus tiekimo grandinėje.
3. Sudaryti rodiklių sistemą, skirtą tiekimo grandinės žiediškumui vertinti.
4. Pasiūlyti žiedinės tiekimo grandinės teorinį modelį.
5. Pasiūlyti ir pritaikyti priemonę norint įvertinti žiediškumo apribojimus, ir identifikuoti galimus apribojimų sprendimus Europos Sąjungos saulės fotovoltikos tiekimo grandinėje.

Tyrimų metodika

Darbo tikslui pasiekti naudota keletas metodų. Literatūros apžvalga buvo pasitelkta analizuojant žiedinės ekonomikos principų taikymą tiekimo grandinėse ir siekiant pasiūlyti rodiklius bei žiedinės tiekimo grandinės teorinį modelį. Pusiau struktūruoti interviu buvo naudojami siekiant surinkti organizacijų vertinimus apie dabartinius ŽTG apribojimus. Interviu transkripcijų kodavimas naudotas žiediškumo apribojimų kategorijoms nustatyti. Siekiant nustatyti rodiklių svorius, taikytas Delphi metodas. Struktūruoti interviu naudoti siekiant nustatyti, kaip organizacijos suvokia žiediškumo apribojimų poveikį rodikliams. Galiausiai, TOPSIS metodas buvo naudojamas žiediškumo apribojimams nustatyti pagal jų poveikį tiekimo grandinei.

Darbo mokslinis naujumas

Vyraujant tyrėjų požiūriui, kai žiediškumo dėmesys sutelkiamas tik į vieną ar kelias organizacijas, šiame darbe valdymo praktika nagrinėjama žiedinės tiekimo grandinės lygmeniu. Siūlomas žiedinės tiekimo grandinės teorinis modelis, kuriame dalyvauja visos ŽTG organizacijos, siekiančios nuolat tobulinti žiediškumą.

Darbe siūlomas rodiklių, skirtų žiediškumui vertinti tiekimo grandinėje, sąrašas. Rodikliais pagrįsta vertinimo priemonė padeda nustatyti svarbiausius ŽE apribojimus tiekimo grandinėje. Sistema apima du rodiklius, kurie yra naujovė mokslinių tyrimų srityje. Jie padeda įvertinti: (1) ar žiediškumo apribojimai daro poveikį organizacijos veiklai ir (2) ar organizacija yra suinteresuota bendradarbiauti sprendžiant apribojimus. Panaudojus rodiklius kartu su TOPSIS metodu galima nustatyti, kurį apribojimą svarbiausia likviduoti norint didinti žiediškumą. Pasiūlytas teorinis modelis leidžia įtraukti visas organizacijas tiekimo grandinėje, siekiant pagerinti žiediškumą. Jis taip pat praplečia vadybos sritį, suteikdamas galimybę sisteminti tiekimo grandinės lygmens informaciją tam, kad būtų galima nustatyti žiediškumo apribojimus ir juos prioritetizuoti.

Darbo rezultatai praplečia apribojimų teorijos taikymą vadybos srityje – nuo gamybinės pramonės aplinkos į žiediškumo apribojimų identifikavimo tiekimo grandinėse. Kiekviena suinteresuotųjų šalių grupė pristatoma tiekimo grandinės etapuose – nuo medžiagų gamintojų iki perdirbėjų. Tyrimo rezultatai rodo, kad sėkmingam žiedinės ekonomikos sistemos tobulinimui tiekimo grandinėse būtinas suinteresuotųjų šalių bendradarbiavimas, jų darbas išvien nustatant apribojimus ir jų poveikį. Rezultatai taip pat nurodo, kad tiekimo grandinės organizacijos, atsižvelgiant į ištekliais pagrįsto požiūrio, priklausomybės nuo išteklių ir žinių valdymo teorijas, turi ribotą galimybę didinti žiediškumą pavienėse organizacijose dėl priklausomybių nuo kitų tiekimo grandinės dalyvių.

Darbo rezultatų praktinė reikšmė

Disertacijos išvadose nurodomi žiediškumą varžantys ES saulės fotovoltikos tiekimo grandinės apribojimai. Pasiūlyta priemonė palengvins valstybių ir organizacijų darbuotojų gebėjimus vertinant žiedinės ekonomikos apribojimus tiekimo grandinėse.

Disertacijos išvados buvo panaudotos rengiant ES programos „Europos horizontas“ RETRIEVE projekto koncepciją, kuri gavo finansavimą iš Europos Sąjungos „Europos horizontas“ mokslinių tyrimų ir inovacijų finansavimo programos pagal dotacijos susitarimą Nr. 101122332 (Reintegration of photovoltaic panel waste back into manufacturing as high value products, n.d.).

Rezultatai taip pat buvo panaudoti teikiant grįžtamąjį ryšį Lietuvos valstybinio audito institucijai „Valstybės kontrolė“, rengiant vertinimo temą „Pasirengimas saulės ir vėjo jėgainių, energijos kaupimo įrenginių atliekų utilizavimui“.

Ginamieji teiginiai

Disertacijoje ginami šie teiginiai:

1. Siūloma žiedinės ekonomikos rodiklių sistema, skirta tiekimo grandinės apribojimų poveikio žiediškumui įvertinti.
2. Siūlomas teorinis modelis, skirtas tiekimo grandinės žiediškumui įvertinti.
3. Siūlomas įrankis, skirtas žiediniams apribojimams vertinti ir identifikuoti jų galimus sprendimus.

Tyrimo rezultatų aprobavimas

Disertacijos tema paskelbti 5 moksliniai straipsniai. Dvi publikacijos paskelbtos mokslo žurnale, įtrauktame į *Web of Science* Science Citation Index Expanded, du straipsniai – kituose tarptautiniuose recenzuojamuose žurnaluose, vienas – recenzuojamoje tarptautinės konferencijos medžiagoje.

Disertacijoje atliktų tyrimų rezultatai buvo paskelbti 4 mokslinėse konferencijose Lietuvoje ir užsienyje:

- International Scientific Conference *Contemporary Issues on Business, Management and Economics Engineering, 13–14 Gegužė 2021, Vilnius, Lietuva.*
- International Scientific Conference *Business and Management 2023*, 11–12 Gegužė 2023, Vilnius, Lietuva.
- International Scientific Conference *40th European Photovoltaic Solar Energy Conference and Exhibition*, 18–22 Rugsėjis 2023, Lisabona, Portugalija.
- International Scientific Conference *41st European Photovoltaic Solar Energy Conference and Exhibition*, 23–27 Rugsėjis 2024, Viena, Austrija.

Doktorantūros studijų metu atlikta mokslinė stažuotė:

- 2023 m., Berno taikomųjų mokslų universitetas, Bielis, Šveicarija.

Disertacijos struktūra

Disertaciją sudaro šios dalys: įvadas, trys pagrindiniai skyriai (Priedas A), bendrosios išvados, literatūros sąrašas, autoriaus mokslinių publikacijų disertacijos tema sąrašas ir priedai. Darbo apimtis be priedų – 160 puslapiai. Rašant disertaciją buvo panaudoti 187 literatūros šaltiniai.

1. Teorinis požiūris į žiedinę tiekimo grandinę: teorijos ir sampratos

Šiame skyriuje apžvelgiama žiedinė ekonomika (toliau – ŽE), nagrinėjant tiekimo grandinės vaidmenį pereinant prie ŽE, pagrindines strategijas, ŽE tiekimo grandinei įtaką darančias teorijas ir sąvokas, svarbiausius veiksnius bei rodiklius, ir pateikiamas žiedinės tiekimo grandinės modelis.

Literatūros apie ŽE ir žiedinę tiekimo grandinę apžvalgoje teigiama, kad organizacijos gali pagerinti žiedinės grandinės veiklos rezultatus (padidinti perdirbimą, pakartotinį naudojimą ir t. t.) bendradarbiaudamos su žiedinės tiekimo grandinės „veikėjais" (Verbanov et al, 2021). Problema, susijusi su žiedinių procesų kūrimu, yra tai, kad organizacijos yra priklausomos viena nuo kitos. Organizacijų tikslai ir jų ŽE strategijos priklauso nuo kitų organizacijų, pavyzdžiui, perdirbėjų, kurie gali užtikrinti didelės vertės perdirbimą ir sugrąžinti medžiagas atgal į sistemą kaip antrines. Perdirbėjo tikslui pasiekti gali trukdyti nestandartizuotas produktų medžiagų sudėties dalijimosi būdas.

ŽE strategijos ir jų metodai mokslinių tyrimų srityje pirmiausia orientuoti į vienos organizacijos perspektyvą (Blomsma et al., 2019). Pasirinkus įgyvendinti tik vienos organizacijos ŽE tikslus, tačiau neįtraukiant kitų tiekimo grandinės organizacijų, neišnaudojamas visas ŽE potencialas, todėl pažanga yra ribota. Taigi metodas, kuris sprendžiant ŽE problemas pasitelkia visos tiekimo grandinės organizacijos, suteikia didžiausią ŽE augimo potencialą (Jørgensen and Remmen, 2018).

Atlikta teorijų ir sampratų apžvalga, siekiant nustatyti teorinius žiedinius tiekimo grandinės įgyvendinimo sprendimus. Aiškiai išreikštos (angl. *explicit*) ir numanomos žinios (angl. *implicit*) atlieka svarbų vaidmenį didinant organizacijų pajėgumą siekti žiediškumo. Panaudojant visas žiedinės tiekimo grandinės žinias, galima plėtoti bendradarbiavimą siekiant išspręsti apribojimus, ribojančius ŽE taikymą organizacijose.

Organizacijų motyvacija dalyvauti koordinuojant žiedinę tiekimo grandinę yra siekis įgyti konkurencinį pranašumą. Norint išmatuoti žiediškumo naudą, kurią organizacija gauna iš žiedinės tiekimo grandinės, reikalingi rodikliai. ŽE vertinti siūlomi rodikliai susiję su produkto perdirbimu, antrinių žaliavų naudojimu, organizacijų motyvacija spręsti apribojimą ir pan. Šie rodikliai skirti matuoti apribojimus pasirinktoje tiekimo grandinėje, siekiant įvertinti, kaip jie veikia tiekimo grandinės žiediškumą.

Siūlomas žiedinės tiekimo grandinės modelis atskleidžia organizacijų vaidmenį sprendžiant apribojimus tiekimo grandinėje. Tai susideda iš apribojimų nustatymo, įvertinimo, bendradarbiavimo ir išsprendimo. Bendras tiekimo grandinės bendradarbiavimas gali daryti poveikį aplinkai, pavyzdžiui, reguliavimo veiksniams, siekiant panaikinti arba skatinti taisykles, kurios leistų geriau išnaudoti ŽE potencialą.

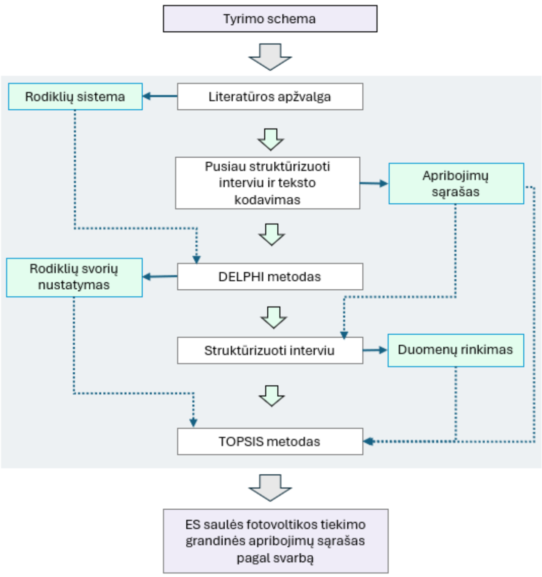
2. Žiedinio ciklo apribojimų nustatymo, įvertinimo ir tinkamiausio apribojimo pasirinkimo metodika

Disertacijos antrą dalį sudaro penki etapai. Pirmasis etapas – rodiklių sistemos pasiūlymas, atsižvelgiant į žiedinės tiekimo grandinės modelį. Antrasis etapas – metodų aprayšimas, kurie buvo naudoti norint panaudoti pasiūlytą priemonę. Trečiajame etape aprašomas žiedinės grandinės apribojimų nustatymo metodas. Ketvirtasis žingsnis apima duomenų rinkimo metodą, leidžiantį įvertinti apribojimų įtaką tiekimo grandinėje. Paskutiniame etape aprašomas rodiklių svorio nustatymo metodas.

Rodikliai, skirti žiediškumui matuoti, buvo sudaryti remiantis literatūros apžvalga ir ISO 59020 standartu (International Organization for Standardization [ISO], 2024). Du papildomi rodikliai grindžiami koordinavimo teorija. Taip pat atsižvelgta į ištekliais pagrįstą požiūrį, siekiant įvertinti organizacijos gebėjimą panaudoti savo išteklius apribojimams spręsti.

Priimant sprendimus buvo taikomas TOPSIS metodas, kuriuo siekta atrinkti aktualiausią ES saulės fotovoltikos tiekimo gradinės žiediškumo apribojimą. Taikant TOPSIS metodą atsižvelgiama ne tik į idealią, bet ir į blogiausią įmanomą situaciją (Hwang & Yoon, 1981). Šiuo atveju alternatyva pasirenkama įvertinant prasčiausius konkrečių apribojimų rodiklių rezultatus.

DELPHI metodo derinimas su TOPSIS sustiprina metodiką, nes užtikrina pakankamą ekspertų dalyvavimą ir leidžią pagrįstai nustatyti rodiklių svorius (Weinert, 1999). Tai ypač svarbu, atsižvelgiant į tai, kad ES saulės fotovoltikos žiedinėje tiekimo grandinėje yra ribota gamybinių organizacijų ekspertų patirtis ir nedidelis kiekis organizacijų, kurios užsiima perdirbimu ar antriniu saulės modulių panaudojimu. Įtraukiant tarptautinių ir išorės ekspertų indėlį, DELPHI metodas sumažina šališkumą ir žiedinėje tiekimo grandinėje egzistuojančias žinių spragas, padidindamas TOPSIS rezultatų patikimumą. DELPHI ir TOPSIS metodų derinys sukuria patikimą sistemą, padedančią spręsti unikalius tyrimo uždavinius. Nors TOPSIS nuolat reitinguoja apribojimus naudodamas objektyvius kriterijus ir jų santykinius svorius, DELPHI užtikrina, kad šie svoriai būtų gauti bendru srities ekspertų sutarimu, atspindinčiu žiediškumo aktualijas industrijoje.



S2.1 pav. Tyrimo etapai ir pasirinkti metodai (sudaryta autoriaus)

ES saulės fotoelektrikos tiekimo grandinės apribojimai buvo nustatyti taikant teksto kodavimo metodą. Naudojant pusiau struktūruotą interviu, buvo apklausta 20 organizacijų. Interviu transkripcijos koduotos naudojant MAXQDA programą, siekiant suskirstyti žiediškumo apribojimus, tikslus ir galimus sprendimus.

Pasitelkiant struktūruoto interviu metodą, apklausta 12 ES saulės fotovoltikos tiekimo grandinės organizacijų. Duomenys apie apribojimus buvo renkami naudojant penkiabalę vertinimo sistemą – nuo vieno (labai mažas poveikis) iki penkių (labai didelis poveikis) balų, siekiant įvertinti, kaip kiekvienas apribojimas veikia kiekvieną rodiklį.

Rodiklių svoriai buvo nustatyti taikant Delphi metodą. Siekiant sužinoti, ar ekspertai sutarė dėl rodiklių svorių, naudotas Kendall W koeficientas (Kendall & Smith, 1939). DELPHI tyrimui buvo pasitelkti 6 ekspertai.

Pasitelkus visų metodų rezultatus, buvo taikytas TOPSIS metodas siekiant prioritetizuoti žiedinius apribojimus ES saulės fotovoltikos tiekimo grandinėje. Tyrimo schema pateikta S2.1 paveiksliuke.

3. Europos Sajungos saulės fotovoltikos tiekimo grandinės žiediškumo apribojimų vertinimas

Saulės fotovoltikos industrija sunaudoja daug išteklių, kurių pagrindiniai yra aliuminis, stiklas, sidabras, varis ir silicis. Europos Sąjungoje (toliau – ES) yra nedidelė tiekimo grandinės koncentracija (PV Manufacturing in Europe,… n.d.). Didžioji dalis (daugiau kaip 90 %) komponentų gaminama Azijoje, daugiausia – Kinijoje. Trys pagrindiniai ES saulės fotovoltikos tiekimo grandinės iššūkiai yra šie: (1) komponentų, reikalingų atsinaujinančiai energijai gaminti, gamyba sutelkta už ES ribų, (2) didelis medžiagų, ypač sidabro ir vario, suvartojimas, (3) nepakankamai išvystyti produkto pabaigos gyvavimo procesai. Ši pramonės šaka yra aktuali kalbant apie žiediškumo naudą, siekiant sumažinti priklausomybę nuo žaliavų kritiškai svarbioje industrijoje.

Po pusiau struktūruotų interviu ir teksto kodavimo, naudojant MAXQDA programą, buvo nustatyti ŽE apribojimai, galimi jų sprendimai ir organizacijų tikslai. Remiantis tekstų kodų skaičiumi iš interviu tekstų, buvo atliktas kodų kategorijų rangavimas. Trys pagrindiniai apribojimai buvo šie: 1) nenuspėjamas pakartotinio naudojimo ir perdirbimo kiekis, 2) nepakankamas tiekimo grandinės bendradarbiavimas ir 3) nepakankamas antrinių žaliavų grynumas, dėl kurio jos negali būti pakartotinai panaudojamos saulės modulių gamyboje. Trys aktualiausi sprendimai, galintys potencialiai išspręsti apribojimus, yra šios: 1) sertifikavimo ir (arba) standartizavimo įgyvendinimas, 2) pramoninio perdirbimo didinimas ir 3) informacijos apie gaminius prieinamumo didinimas. Trys svarbiausi ES saulės fotovoltikos organizacijų tikslai, susiję su žiediškumu, yra šie: 1) ciklo uždarymas, 2) anglies pėdsako mažinimas ir 3) Europos perdirbimo verslo plėtra. Rezultatai rodo, kad šioje pramonės šakoje yra įvairių žiediškumo problemų ir galimų jų sprendimo būdų.

Siekiant nustatyti rodiklių svorius, buvo surengti du Delphi raundai. 6 ekspertai įvertino 9 rodiklius. Po pirmojo turo buvo pašalinti 2 rodikliai: biomasės kiekis ir recirkuliacija biologiniame cikle. Šie du rodikliai nebuvo reikšmingi saulės fotovoltikos pramonei dėl medienos ar panašaus atsinaujinančio turinio nebuvimo. Po pirmojo raundo W koeficientas buvo 0,30 (iš 1) – kuo arčiau 0, tuo mažiau ekspertų sutaria dėl to, kurie rodikliai yra svarbesni už kitus. Antrojo raundo pabaigoje W koeficientas buvo 0,72, o tai nurodo reikšmingą ekspertų nuomonių suderinamumą.

Siekiant surinkti duomenis iš ES saulės fotovoltikos žiedinės tiekimo grandinės dalyvių, 5 balų sistemoje – nuo 1 (mažas poveikis) iki 5 (didelis poveikis) struktūruotai apklausta 12 organizacijų atstovų. Rezultatai rodo, kad pakartotinio komponento naudojimo naujame produkte veikla sunkiai pasiekiama dėl besikeičiančių technologijų ir komponentų dydžių. Atsižvelgiant į 25–30 metų saulės modulių eksploatavimo trukmę, sunku naudoti antrinius komponentus naujuose saulės moduliuose. Tačiau apklaustieji sutinka, kad svarbu žinoti tam tikrą informaciją apie saulės modulius, pavyzdžiui, iš kokių medžiagų jie pagaminti, siekiant užtikrinti jų tinkamą perdirbimą ateityje.

Taikant TOPSIS metodą – norint nustatyti, kuris apribojimas yra svarbiausias – pirmoje vietoje atsidūrė neryžtingas keitimasis informacija. Šis apribojimas susijęs su kitais apribojimais, pavyzdžiui, saulės modulių atsekamumo nepakankamumu. Apribojimai pavaizduoti S3.1 lentelėje. Pirmoje vietoje esančio apribojimo sprendimas remiasi politikos priemonėmis ir duomenų dalinimusi, o pramonės atstovai turi įgyvendinti keitimosi informacija sprendimus.

S3.1 lentelė. Apribojimų eiliškumas nuo didžiausio iki mažiausio pagal TOPSIS metodo įvertinimą

Apribojimai	**TOPSIS įvertinimas**	**Reitingavimas**
Neryžtingas keitimasis informacija	0,974	1
Nepakankamas saulės modulių atsekamumas	0,867	2
Prastas logistikos tvarkymas atvirkštinėje tiekimo grandinėje	0,747	3
Neteisėtas netinkamų saulės modulių eksportas už ES ribų	0,731	4
Neprognozuojami saulės modulių pakartotinio panaudojimo ir perdirbimo kiekių duomenys	0,661	5
Nesuderinti teisės aktai visoje Europoje	0,627	6
Įprastinis saulės modulių perdirbimas yra nepelningas	0,364	7
Nepakankamas perdirbtų medžiagų grynumas, trukdantis jų pakartotiniam panaudojimui saulės modulių gamyboje	0,326	8
Neišvystyti perdirbimo metodai sumažina perdirbtų žaliavų kokybę	0,184	9
Nepakankamas tiekimo grandinės bendradarbiavimas	0,182	10

Kadangi neryžtingo keitimosi informacija efektyvumo koeficientas buvo 0,974 (iš 1), tai parodė, kad beveik visiškai sutariama, kuriam apribojimui reikia teikti pirmenybę. Mažiausiai aktualus apribojimas yra nepakankamas tiekimo grandinės bendradarbiavimas. Šis apribojimas yra sunkiai išsprendžiamas, nes pati industrija nėra suinteresuota tobulinti žiedinius procesus, kadangi didžioji tiekimo grandinės dalis yra Kinijoje.

Bendrosios išvados

1. Literatūros apžvalga atskleidė sudėtingą žiedinių tiekimo grandinių sistemą. Norint užtikrinti žiediškumą bet kurioje pramonės šakoje, reikia daugelio suinteresuotųjų subjektų bendradarbiavimo. Žiedinės tiekimo grandinės dalyvių poveikis kaupiasi visoje grandinėje, todėl tolesnių grandinės dalyvių galimybės didinti žiediškumą yra ribotos. Integruojant žinias iš visų žiedinės tiekimo grandinės etapų, galima išsamiai apžvelgti žiediškumo problemas ir pasiūlyti galimus jų sprendimus.
2. Darbe išplečiamas apribojimų teorijos taikymas ŽTG sistemai. Taip pat analizuojamos priklausomybės nuo išteklių bei jais pagrįsto požiūrio teorijos, siekiant nustatyti, kokių gebėjimų ir resursų reikalauja žiediškumo gerinimas tiekimo grandinėje. Žinių valdymo teorija nagrinėjama tam, kad būtų galima identifikuoti reikalingą informaciją ir suprasti, kaip ją efektyviai valdyti, siekiant didinti tiekimo grandinės žiediškumą.
3. Remiantis literatūros apžvalga ir ISO 59020 standartu, buvo pasiūlyta rodiklių sistema žiedinės ekonomikos apribojimams įvertinti. Šie rodikliai, pavyzdžiui, perdirbtas arba pakartotinai panaudotas medžiagų kiekis produkte, yra universalūs rodikliai, taikytini daugumai pramonės šakų. Remiantis bendradarbiavimo teorija ir ištekliais pagrįstu požiūriu, buvo įtraukti du papildomi apribojimai: apribojimo poveikis organizacijos žiediškumo potencialui ir organizacijos suinteresuotumas spręsti šį apribojimą. Sudėjus rodiklius į vieną sistemą, galima įvertinti įvairių rūšių apribojimus, kurie gali būti skirtingi, priklausomai nuo pasirinktos pramonės šakos.
4. Apribojimų, ištekliais pagrįsto požiūrio, priklausomybės nuo išteklių ir žinių valdymo teorijos buvo integruotos į žiedinės tiekimo grandinės teorinį modelį. Teorinio modelio tikslas – pagerinti tiekimo grandinės žiediškumą, vienodai įtraukiant visas organizacijas į apribojimų vertinimą. Disertacijoje daugiausia dėmesio skiriama pirmiesiems dviem žingsniams – apribojimų nustatymui ir vertinimui.
5. Siūlomą priemonę sudaro rodiklių sistema, skirta tiekimo grandinės žiediškumui vertinti. Pritaikius šią priemonę, nustatyta 20 ES saulės fotovoltikos tiekimo grandinės apribojimų. Apribojimai yra įvairūs – nuo bendradarbiavimo iki technologinių iššūkių. 19 apribojimų buvo paminėti bent 2 skirtingų tiekimo grandinės etapų atstovų, o tai rodo, kad beveik nė vieno apribojimo organizacijos negali išspręsti pačios.
6. Taikant TOPSIS metodą, buvo nustatytas didžiausią poveikį darantis apribojimas – neryžtingas keitimasis informacija. Kadangi didžioji dalis saulės fotovoltikos medžiagų, komponentų ir produktų gamybos vyksta Azijoje, informacijos prieinamumas yra ribotas. Šiam apribojimui išspręsti galima taikyti teisinį reguliavimą su Europos Komisijos planuojamu produkto ekologiniu projektavimu, skaitmeniniais gaminių pasais arba „Net-Zero Industry Act“. Priešingu atveju,

kaip rodo rezultatai, ES saulės fotovoltikos tiekimo grandinės organizacijos neįveiks šio apribojimo, nes jų galimybės daryti įtaką Azijos tiekimo grandinei yra ribotos.

7. Disertacijos rezultatai leido nustatyti veiksnius, kurie gali tapti tolesniais žingsniais siekiant užmegzti bendradarbiavimą ir spręsti apribojimus. Palyginti su kitų tyrėjų darbais, skirtais saulės fotovoltikos žiediškumo problemoms nustatyti ir analizuoti, šiame tyrime vienodai įtraukiami skirtingi ES saulės fotovoltikos tiekimo grandinės dalyviai, sujungiant jų įžvalgas (apribojimus, sprendinius, tikslus), siekiant nustatyti svarbiausią ŽE apribojimą.

Tadas RADAVIČIUS

ASSESSMENT OF CIRCULARITY CONSTRAINTS
IN THE EUROPEAN UNION'S PHOTOVOLTAICS SUPPLY CHAIN

Doctoral Dissertation

Social Sciences,
Management (S 003)

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Daktaro disertacija

Socialiniai mokslai,
Vadyba (S 003)

Lietuvių kalbos redaktorė Deimantė Grigaitė

Anglų kalbos redaktorė Jūratė Griškėnaitė

2025 04 14. 14,5 sp. l. Tiražas 20 egz.
Leidinio el. versija *https://doi.org/10.20334/2025-018-M*
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